Evaluation of BC Rougheye Rockfish (*Sebastes aleutianus*) and Canary Rockfish (*Sebastes pinniger)* in reference to COSEWIC criteria.

Technical report for Fisheries and Oceans Canada

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Introduction

The implementation of the federal Species at Risk Act (SARA) begins with an assessment of the risk of species extinction by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Fisheries and Oceans Canada (DFO) supports COSEWIC with the best available information with which to obtain an accurate assessment for each species.

Many fish species are lacking sufficient data (*e.g*. relative abundance indices or absolute abundance survey data) to conduct a fishery stock assessment or data are yet to be processed to update a stock assessment. In these cases more simplistic management procedures may be considered (e.g. a size limit). Additionally in some instances more simple management procedures can provide similar performance to complex assessments but have the advantage that they are easier to apply, require fewer data, and are easier for stakeholders and reviewers to understand.

The performance of any proposed management procedure (MP)(*e.g*. catch limits set by a stock assessment linked to a 40-10 harvest control rule, the same assessment linked to a 60-20 rule, use of mean historical catches as the catch limit *etc*) is likely to be strongly determined by a number of factors including the life-history of the species, its current stock level relative to a productive state, the quality of the data available, the types of data available, management objectives, ability to enforce management recommendations (*e.g*. a size limit versus a catch limit), fishery dynamics and the pattern of historical exploitation. Currently the only coherent basis for deciding what management approach to take prior to implementation is to test prospective management approaches with simulated population and fishery dynamics (*e.g*. a Management Strategy Evaluation approach (MSE), Butterworth and Punt 1999, Punt *et al*. 2016).

The Data Limited Methods toolkit (DLMtool v3.2.3, Carruthers and Hordyk 2017) is an R package designed to simulation test fishery management procedures subject to the various uncertainties in stock dynamics, fishery dynamics and data quality (*e.g*. Carruthers *et al*. 2015, Harford and Carruthers 2017). These components are formalized in an operating model which represents credible scenarios for real system dynamics.

In this application of DLMtool, operating models are constructed for two rockfish species in BC waters: rougheye rockfish (*Sebastes aleutianus*) and canary rockfish (*Sebastes pinniger*). Using these operating models, management procedures are tested by MSE whereby, over many future projected years, MPs are applied iteratively to generate recommendations (*e.g*. catch limits) which are imposed on the simulated stock. When many varied stock histories and future projections are simulated it is possible to evaluate the performance of the management procedures with respect to:

(1) other management procedures (to identify the most suitable approaches),

(2) the characteristics of the system (to identify the important system characteristics that are driving performance) and

(3) the quality of data (to identify those data which if improved are most likely to offer the biggest benefits to management).

In addition to finding appropriate management procedures for canary and rougheye rockfish we also establish preliminary protocols for conducting COSEWIC assessments using the DLMtool simulation framework and also establish which data and uncertainties are most critical to management.

1 Methods

1.1 Development of operating models

In-depth descriptions of operating model specifications for rougheye rockfish and canary rockfish are available in Appendices I and II, respectively. Here we provide a brief review of operating model development.

No formal stock assessment is available for BC rougheye rockfish with which to define operating models. The closest documents available are Haigh et al. (2005, Research Document 2005/096) and Schnute et al. (1999, Research Document 99/184). Since neither document offers an insight into historical patterns in fishing mortality rate or trends in stock size, a custom stock reduction analysis (function *StochasticSRA*) was developed in the DFODLM R package that reconstructs historical stock trends and exploitation to fit catch composition data. The method is similar to that of Walters et al. (2006) and uses a Metropolis-Hastings Markov Chain Monte Carlo (MCMC) algorithm to estimate unfished recruitment, asymptotic selectivity parameters and historical recruitment deviations. Using this approach, a series of simulations are carried out in which growth, natural mortality rate and recruitment parameters are sampled and an MCMC simulation is carried out for each. Once convergence of the algorithm has been confirmed for all simulations, the final MCMC iteration of each simulation is retained. This approach is used to populate approximate ranges for parameters in the rougheye rockfish operating model. Additionally, the stochastic SRA also preserves parameter and time series correlations between natural mortality rate, growth, historical fishing mortality rates, unfished stock size and stock trends.

The stochastic SRA method was applied to rougheye catch-at-age composition and historical annual catch data. The resulting model predictions are included in Appendix I. The principal finding of the stochastic SRA method was that the catch composition data were indicative of a population that has not undergone heavy exploitation due to the relatively high frequency of observations of older fish. Current stock depletion was estimated in the range of 0.45 – 0.9 of unfished levels. Historical exploitation rates were predicted to be relatively low (less than 2% annual harvest rate) with a peak in the early 90's after which they stabilized at around 70% of the maximum level.

Operating model specification for canary rockfish was more straightforward given the availability of a fairly recent stock assessment (Stanley et al. 2009, Research Document 2009/013). In this case parameter ranges, historical exploitation rates were taken from the assessment.

1.2 Testing management procedures

The current version of DLMtool includes over 100 management procedures including simple stock assessments, size limits, effort controls, spatial controls and algorithmic management procedures (e.g. adjusting catch limits based on the gradient in current relative abundance). For both canary and rougheye rockfish operating models, all available MPs were subject to preliminary simulation testing for just 50 years and 100 simulations to reduce candidate MPs to a much smaller fraction (note this number of simulations is still sufficient to obtain reasonably stable MP rankings even if absolute performance is not stable). Reducing the number of MPs is necessary to: lower computational overhead when running the detailed simulations and also to make results easier to visualize and understand.

Performance of MPs was determined over a projected time period of the minimum of 100 years of three generation times following other COSEWIC recovery potential assessments (Anon, 2012; SAR 2011/060). Performance was evaluated based on two metrics that represent biological and fishery sustainability considerations:

(1) the probability of staying above 50% of SSBMSY (spawning stock biomass at maximum sustainable yield) (B50) and
(2) the probability of achieving greater than 50% MSY yield (LTY).

These performance metrics have been used elsewhere in the selection of data limited management procedures in federal US fisheries in the Caribbean and Gulf of Mexico (NOAA SEDAR 46, SEDAR 49).

1.3 Quantifying COSEWIC criteria

Previous recovery potential assessments (Anon 2012; SAR 2011/060) have identified 17 tasks which are used here as a framework for evaluating DLMtool outputs with respect to stock status, threats to recovery and feasibility of recovery. Some of these tasks are outside the scope of this research but others relating to status and trajectory can be addressed.

Historical stock trends were summarized with respect to SSBMSY and 50% of SSBMSY levels. Future projected stock trends were considered under current exploitation rates for a projected time period that was the minimum of 100 years or three generation times (mean generation time: the average age of a mature individual under unfished conditions). To frame the projection of current exploitation rate: two reference management options were also projected: fishing at FMSY levels and zero catches. In addition to MSY reference points, an additional biomass reference point was calculated to represent very low stock sizes, *Blow*. This was the spawning biomass level at which the stock takes more than three generation times to reach 50% BMSY (a recovery target) given zero catches (*i.e*. an extremely low stock level, typically below 1% of unfished stock size for a fish species a long lived as rockfish).

1.4 Quantifying value of information

Let's assume that 100 simulations are undertaken using DLMtool and each simulation has a historical stock trend and catch time series both generated from a sample of life history parameters and also observation properties (e.g. bias and imprecision in observed catches). It is possible to summarise the performance of a management procedure over each simulation and correlate this with the sampled parameters for each simulation. For example, often it is revealed that the sampled bias in catches strongly affects the performance of catch-limit MPs while imprecision in catches (observation error) is much less important.

Similarly it is possible to identify which operating model life-history parameters most strongly determined performance revealing which of the current uncertainties is most consequential for management. Another type of value of information relates to data that are not currently collected but if they were, would allow for the use of new management procedures that perform better. It follows that there are three classes of value of information:

(1) value of better data (e.g. less biased / more precise / greater number of observations)
(2) cost of current uncertainties (which operating model parameters most strongly affect performance)
(3) value of additional data (e.g. a new data source not currently collected but simulated)

It is conceivable that data could be processed for canary rockfish and rougheye rockfish that cover most of the major classes of data (they are potentially not data-poor in the strictest sense) including age and length observations, effort data, relative abundance series, even potentially an estimate of current absolute abundance from a calibrated survey (or fishery CPUE uprated by a catchability estimate from stock assessment). Consequently only analyses 1 and 2, value of information/cost of current uncertainties are considered here.

When quantifying 'value' we consider three possible definitions of utility, probability of exceeding biomass targets (B50), probability of obtaining sustainable long term yield (LTY).

2 Results for Rougheye Rockfish

2.1 Performance of available management procedures

Since current rougheye rockfish depletion was simulated at healthy stock sizes (generally higher than BMSY) the preliminary satisficing simulations revealed a large number of management procedures that offer reasonable performance including many 'status quo' approaches such as average historical catches (*AvC*) and current fishing exploitation rate (*CurE*)(Figure 1).

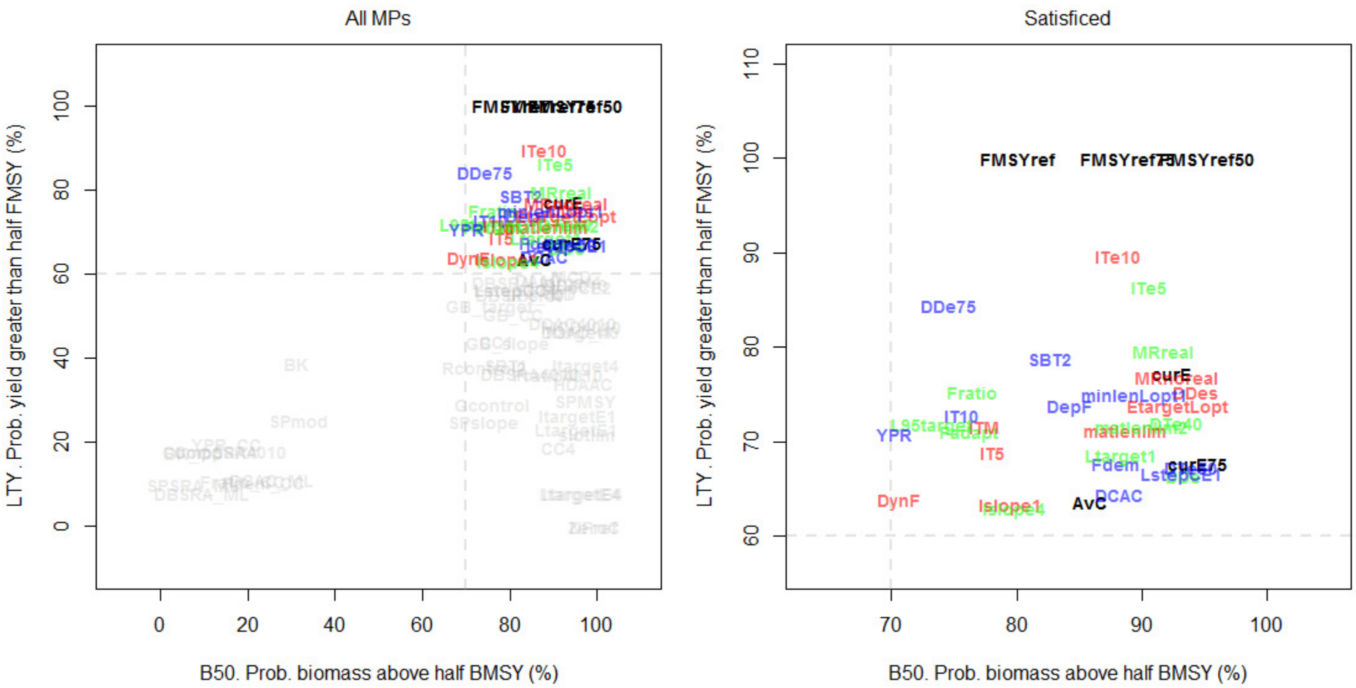

Figure 1. Satisficing of MPs for rougheye rockfish. A total of 30 MPs passed the satisficing requirements of 80% probability of biomass being over 50% BMSY and 70% probability of yield higher than half FMSY yield (dashed lines). MPs that did not meet the satisficing requirements are shaded in grey in the left hand panel. These satisficing requirements were arbitrary and chosen only to reduce the total number of MPs to a manageable set for more detailed analysis. MPs colored black are reference MPs such as current effort and FMSY. The other color coding is arbitrary and simple to improve legibility. The simulations in this case were run for 50 projected years and only 100 simulations were used to generate the metrics (MPs rankings were stable, Appendix IV).

In general, all of the MPs performed worse over the longer simulated time period of the detailed MSE run (100 vs 50 years). The detailed MSE revealed that simple effort control MPs could perform similarly to FMSY reference MPs[2]. These included *ITe10*[3] and *ITe5*.[4]

Simple stock assessment methods such as a deterministic delay-difference assessment providing effort recommendations *DDes,* provided higher certainty of higher biomass levels but at the cost of some yield performance. All other MPs were

[2] The reference MPs: *FMSYref* is fishing at true FMSY levels and F*MSYref75* / *FMSYref50* are MPs fishing at 75% and 50% of FMSY levels, respectively.

[3] *ITe10* is an MP that aims to obtain a pre-specified abundance index (CPUE, survey) level that corresponds with a roughly productive stock size. In DLMtool is assigned a potential range of bias by the user that depends on how credibly an index follows relative abundance and has been indicative of historical stock trends.

[4] *ITe5*: As *ITe10* but with up to a 5% change in fishing effort between years.

'dominated' by these thee, in that they provided both worse yield and lower biomass expectation than the performance frontier of these three MPs. It is worth noting however that maintaining the current fishing effort level (current fishing exploitation rate) *CurE* comparable performance could be obtained. Fishing at average catch levels *AvC*, however was substantially worse in both expected yield and biomass performance metrics.

Other management procedures that offered a reasonably good compromise between yield and biomass considerations were *MRreal*[5], *EtargetLopt*[6] and *matlenlim*[7].

Note that there is limited scope for much improved performance in these metrics by MPs that are currently not available, perhaps as much as a 5% increase in simulations obtaining half FMSY yield and 5% increase in the likelihood of remaining above 50% BMSY.

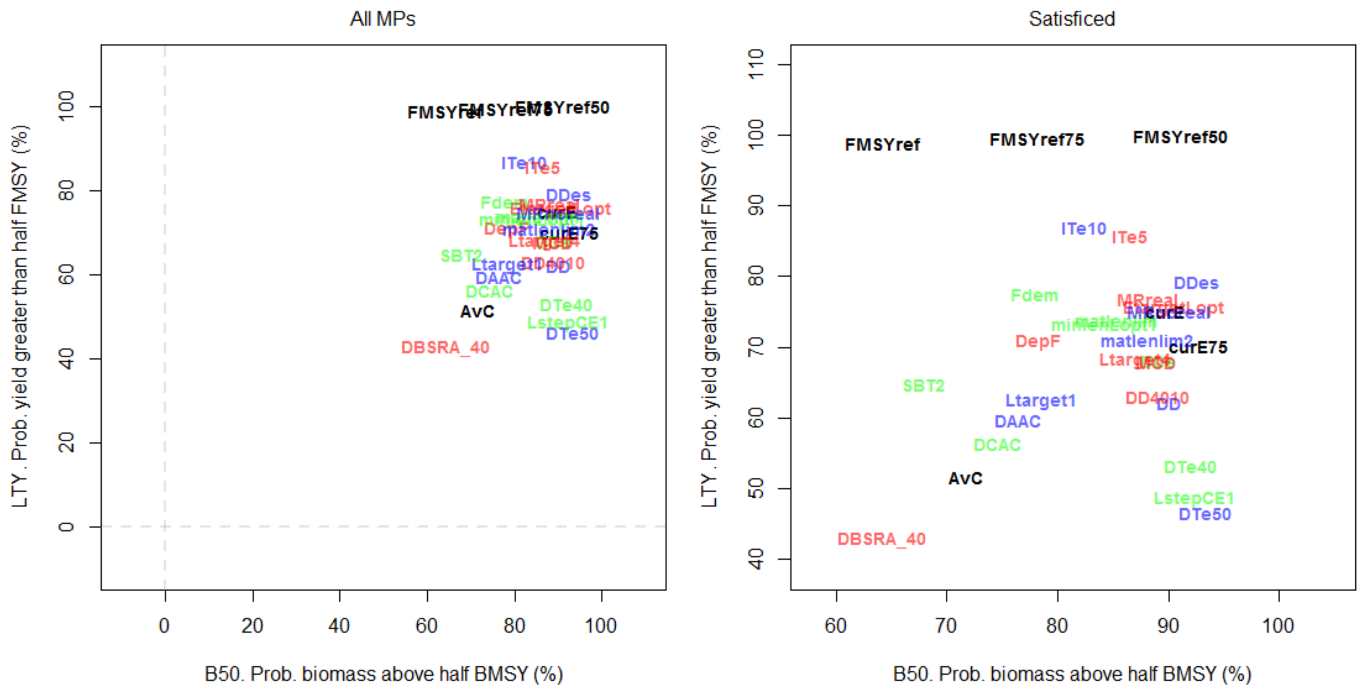

Figure 2. Detailed MSE analysis for rougheye rockfish. MPs colored black are reference MPs such as current effort and FMSY. The other color coding is arbitrary and simple to improve legibility. The simulations in this case were run for 100 projected years and 200 simulations were used to generate the metrics (absolute performance of MPs was stable, Appendix IV)

[5] *MRreal* is a marine reserve in area 1 (in this operating model this is 10% of the habitat with between an 85% and 95% probability of remaining in the area among years, see Appendix I)

[6] *EtargetLop* adjusts fishing effort to achieve a target mean length in the catches

[7] *matlenlim* is an MP that enforced (without implementation error or dead discarding) a size limit that follows exactly the maturity at length ogive.

2.2 Evaluation by COSEWIC criteria

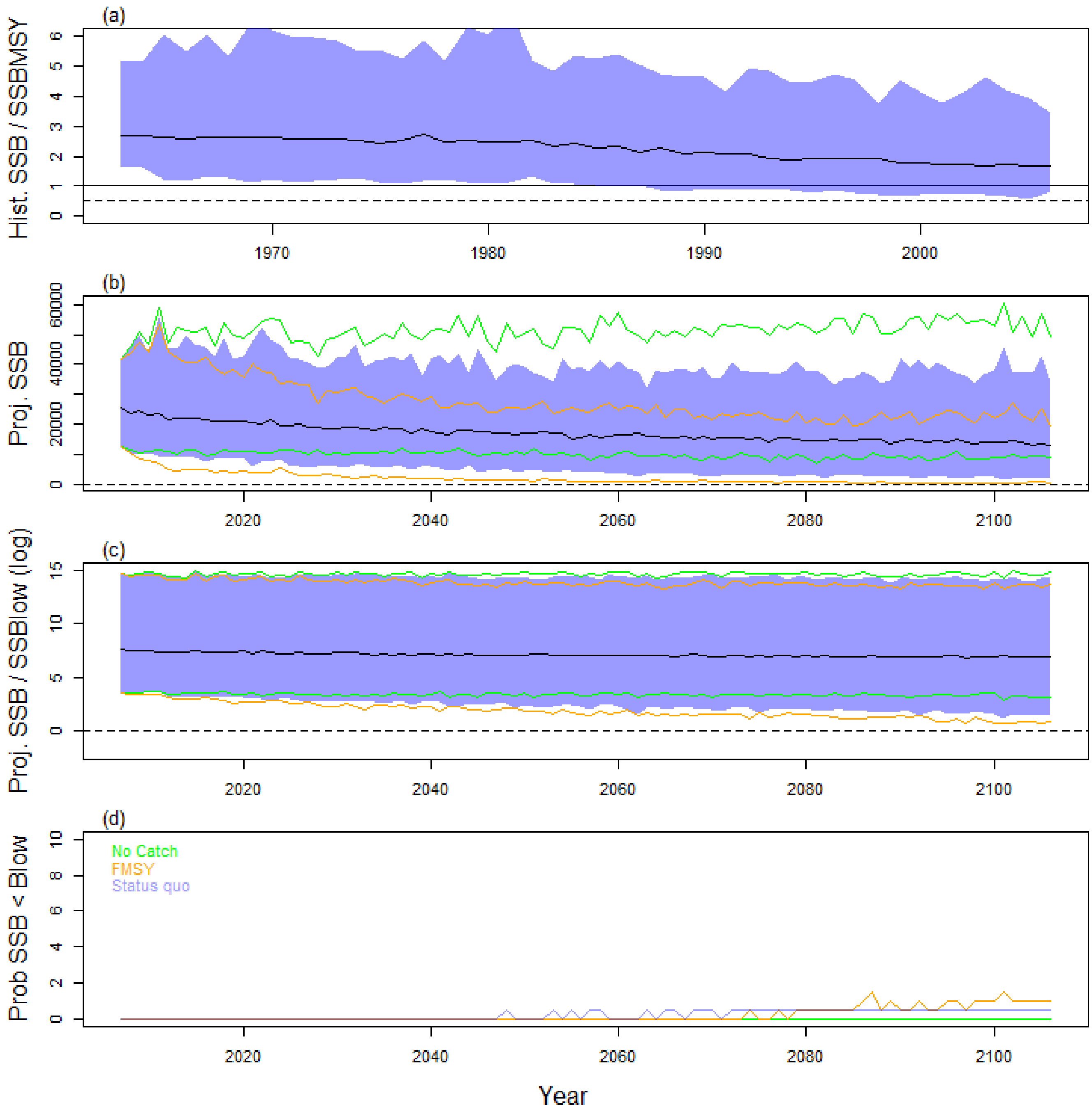

Figure 3. Population trajectories for rougheye rockfish. Panel a shows historical model predicted SSB relative to SSB at MSY levels. Panel b shows projected SSB under status quo exploitation rates, fishing at FMSY and also zero fishing (no catch). Panel c shows the projected SSB relative to a very low biomass level (Blow) where it would take 3 generation times to reach half of SSB at MSY with zero catches. Panel d shows the projected probability of SSB dropping below the Blow threshold.

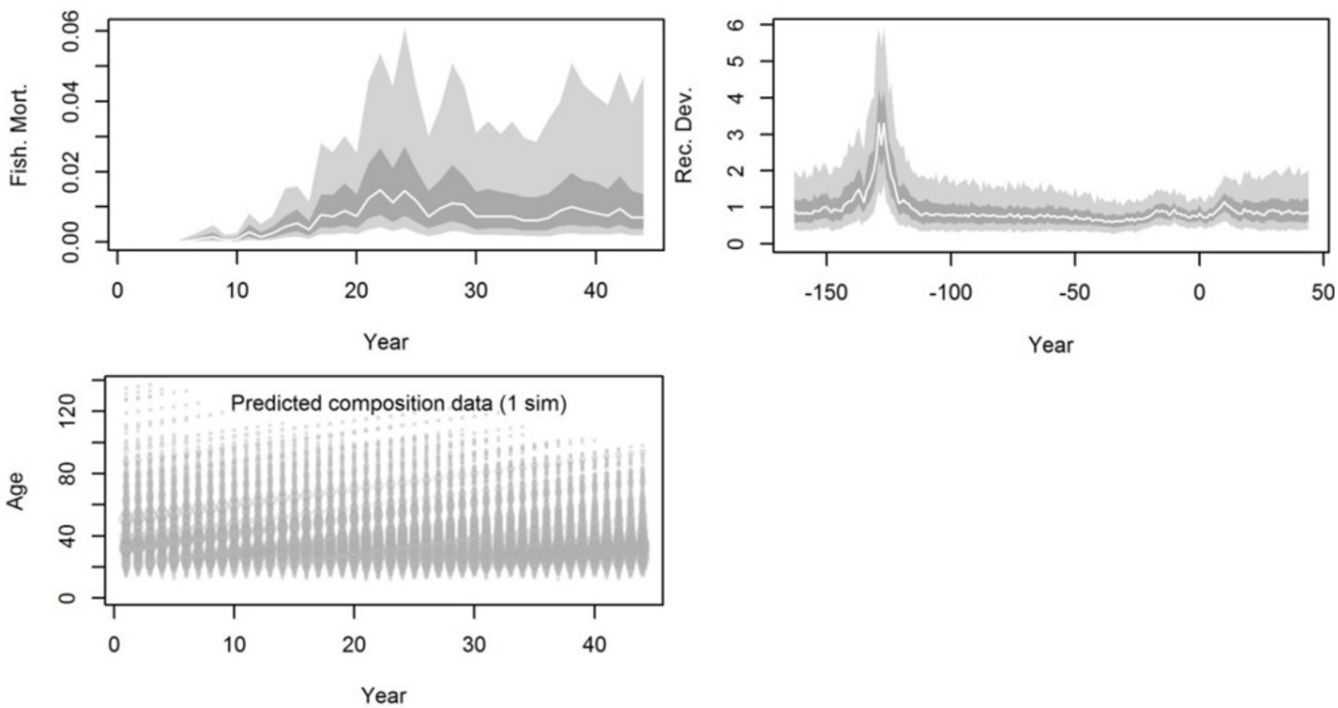

Figure 4. Stochastic SRA predictions of fishing mortality rate, recruitment anomalies and population age structure for rougheye rockfish. In this context, fishing mortality rate refers to the apical F value, the instantaneous fishing mortality rate on age classes of maximum vulnerability. Operating model years are labelled relative to 1971 (i.e. 40 corresponds with 2011, 30 with 2001 etc).

1. Evaluate present species status for abundance, range and number of populations.

The Stochastic SRA conditioning of the rougheye operating models predicts healthy current (2015) stock sizes (Figure 3, panel a) between 46.1% and 86.7% of spawning stock biomass at unfished levels. Note however that the Stochastic SRA receives all its information about depletion from the age composition data and is not informed by a relative abundance index (see Discussion, below).

Outside the scope of this study: 'range and number of populations'

2. Evaluate recent species trajectory for abundance, range, and number of populations

Stochastic SRA predicts very gradual declines in the population with a mean estimated spawning biomass from approximately 3 times MSY levels in 1963 to 2 times MSY levels in 2015. The probability of the stock being in an overfished state (SSB < SSBMSY) increased from less than 1% in 1963 to around 10% in 2015.

Outside the scope of this study: 'range and number of populations'

3. Estimate, to the extent that information allows, the current or recent life history parameters for the species (total mortality [Z], natural mortality [m], fecundity, maturity, recruitment, etc.) or reasonable surrogates, and associated uncertainties for all parameters.

The outputs of the stochastic SRA analysis are available in Appendix I and an excerpt of relevant quantities is presented in Figure 4 above. Current fishing mortality rate estimates (apical *F*) are estimated in the range of 0.0025 to 0.05 (95% probability interval).

Figure 4 shows the relative recruitment strength estimated by stochastic SRA. These are anomalies from the predicted recruitment arising from Beverton-Holt stock recruitment dynamics of comparable steepness to the canary rockfish assessment (0.45 - 0.8, see Appendix I). In general recruitment has been relatively stable and there is little evidence for regime shifts or dominant age classes over the last 50 years.

Natural mortality rate is an input to the operating model and not estimated. The existing review document (Haigh *et al.* 2005) states a point value of M of 0.035 y^{-1} (page 12) for both male fish and females aged 0 - 13. In the operating model this was bracketed by +/- 20% leading to a mean M in the range of 0.028 – 0.042. This is close to the range determined by McDermott (1994) (0.03-0.04) which is referenced in the review document in Section 3.4.2.

Maturity and fecundity were also inputs to the operating model and combined point estimates from the review document (Haigh et al. 2005) with Robin Hood (Punt et al. 2011) borrowing of characteristics (such as slope of the maturity ogive) from the canary rockfish assessment (Stanley et al. 2009)

4. Address the separate terms of reference for describing and quantifying (to the extent possible) the habitat requirements and habitat use patterns of the species.

Outside the scope of this study.

5. Estimate expected population and distribution targets for recovery, according to DFO guidelines.

Spawning biomass levels relative to MSY and 50% MSY levels are presented in Figure 3 panel a.

6. Project expected population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current population dynamics parameters and associated uncertainties using DFO guidelines on long-term projections.

In the case of rougheye rockfish, mean generation time (the average age of an adult in the unfished population) is 45.9 years putting three generation times well over a 100 year horizon. Given observed changes in ecosystem dynamics and oceanographic conditions over such time scales, a limit of 100 projected years was placed on projections.

Current fishing levels are predicted to lead to continued but very shallow declines in SSB over the next 100 years. The probability of the stock dropping below BMSY levels is around 50% but the likelihood of declines to lower than *Blow* levels is negligible and less than 0.5% (Figure 3, panels c and d). Currently exploitation levels are lower than FMSY and are predicted to lead to lesser stock declines.

7. Evaluate residence requirements for the species, if any.

Outside the scope of this study.

8. Assess the probability that the recovery targets can be achieved under current rates of population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

The Stochastic SRA analysis predicts biomass levels much higher than BMSY levels and given this, recovery measures are probably not applicable.

9. Quantify to the extent possible the magnitude of each major potential source of mortality identified in the pre-COSEWIC RAP and considering information in the COSEWIC Status Report, from DFO sectors, and other sources

Outside the scope of this study.

10. Quantify to the extent possible the likelihood that the current quantity and quality of habitat is sufficient to allow population increase, and would be sufficient to support a population that has reached its recovery targets (using the same methods as in step 4).

Outside the scope of this study.

11. Assess to the extent possible the magnitude by which current threats to habitats have reduced habitat quantity and quality.

Outside the scope of this study.

12. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all feasible measures to minimize/mitigate the impacts of activities that are threats to the species and its habitat (steps 9 and 11).

Section 2.1 identifies and evaluates a range of potential management procedures for rougheye rockfish. The feasibility of these management procedures (*i.e.* processing the required data, allocation of capacity *etc*) is not considered.

13. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all reasonable alternatives to the activities that are threats to the species and its habitat (steps 9 and 11), but with potential for less impact. (e.g. changing gear in fisheries causing bycatch mortality, relocation of activities harming habitat).

See Section 2.1 above.

14. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all reasonable and feasible activities that could increase the productivity or survivorship parameters (steps 3 and 8).

Outside the scope of this study (also I'm not certain what is meant by 'survivorship parameters')

15. Estimate, to the extent possible, the reduction in mortality rate expected by each of the mitigation measures in step 12 or alternatives in step 13 and the increase in productivity or survivorship associated with each measure in step14.

See section 2.1. above.

16. Project expected population trajectory (and uncertainties) over three generations (or other biologically reasonable time), and to the time of reaching recovery targets when recovery is feasible; given mortality rates and productivities from 15 that are associated with specific scenarios identified for exploration. Include scenarios which provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.

For alternative approaches this is covered in section 2.1., for current exploitation rate this is also presented in Figure 3 above.

17. Recommend parameter values for population productivity and starting mortality rates, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.

This is the objective of defining operating models and is covered in detail in Appendix I. Also see Value of Information Section 0 below.

2.3 Value of information

Since current exploitation rates are estimated to be less than FMSY and stock levels well above BMSY levels, the quality of data and uncertainties in the current operating model parameters are generally not critical in determining performance of the various MPs (flat and scattered patterns among simulations in the space of sampled parameters and utility). In other words, the top performing MPs can reliably achieve over 50% BMSY and 50% FMSY yields regardless of simulation conditions. This is true of both biomass (Figure 5 and Figure 6) and yield utility metrics (Figure 7 and Figure 8).

2.3.1 Utility according to biomass criteria (B50)

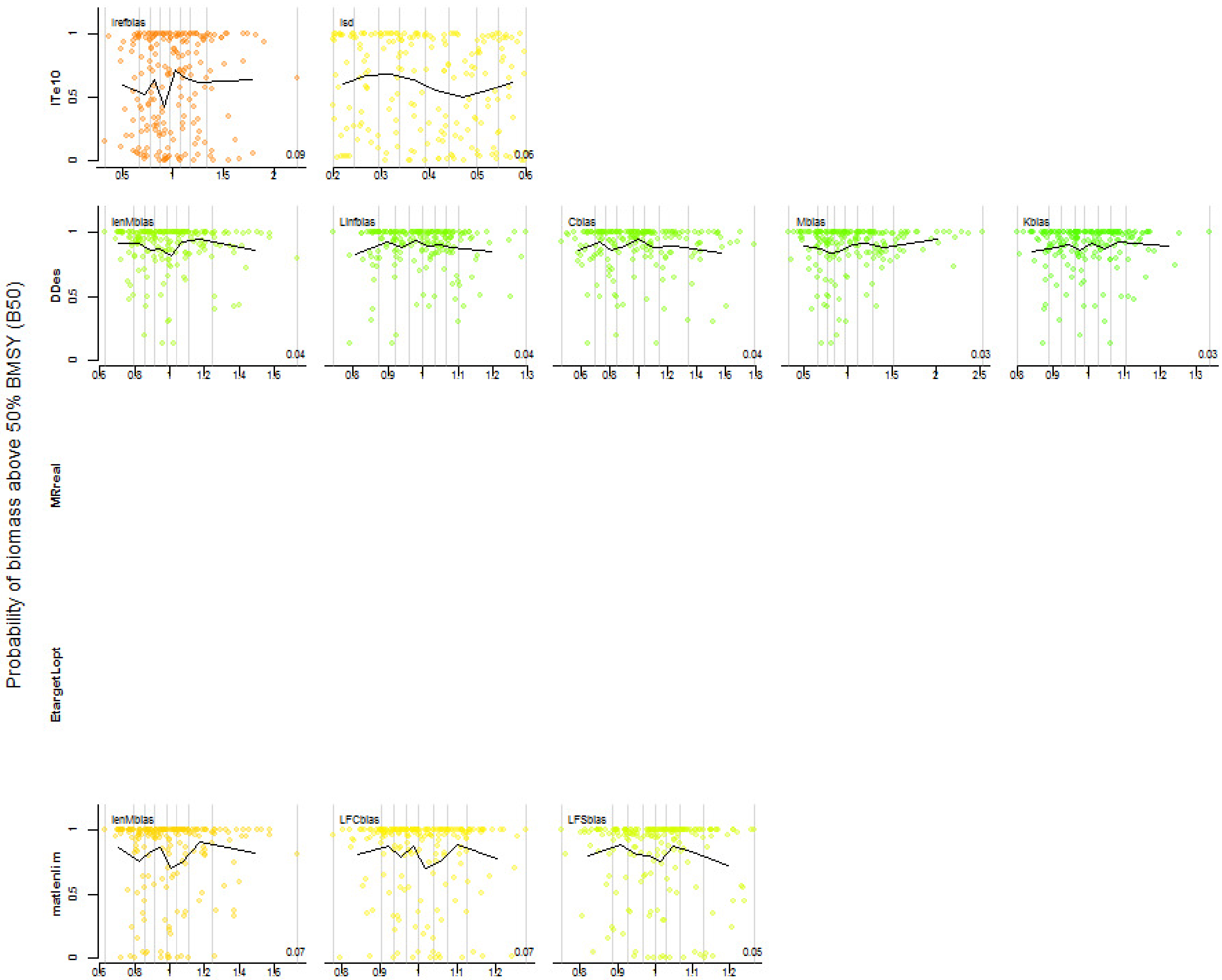

Figure 5.The value of better data for rougheye rockfish top ranking MPs given the biomass utility measure B50. Note that some management procedures do not require data and are prescriptive such as MRreal (closure of area 1 with reallocation of effort to area 2) and EtargetLopt.

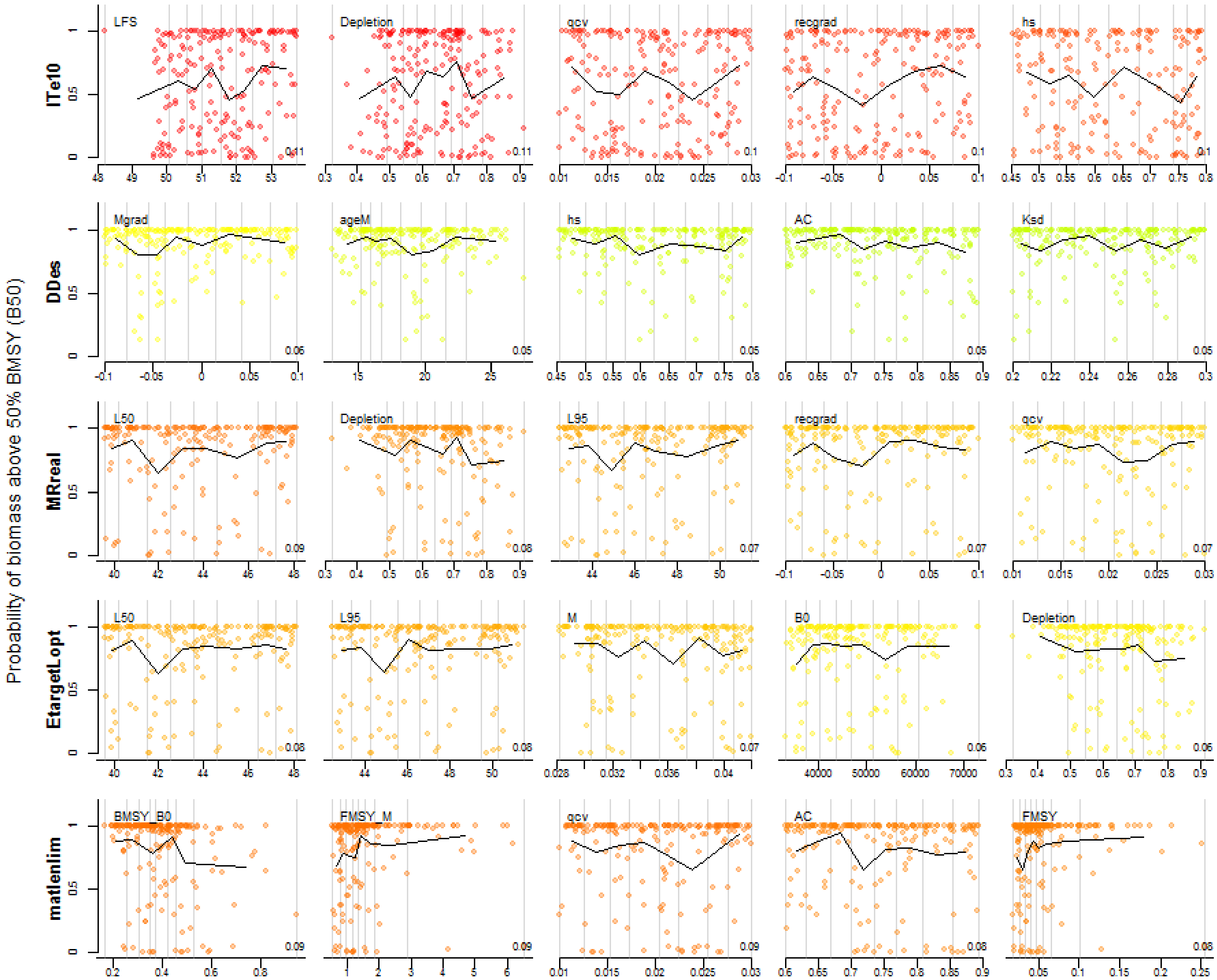

Figure 6. The cost of current uncertainties for rougheye rockfish top ranking MPs given the biomass utility measure B50.

2.3.2 Utility according to long term yield (LTY)

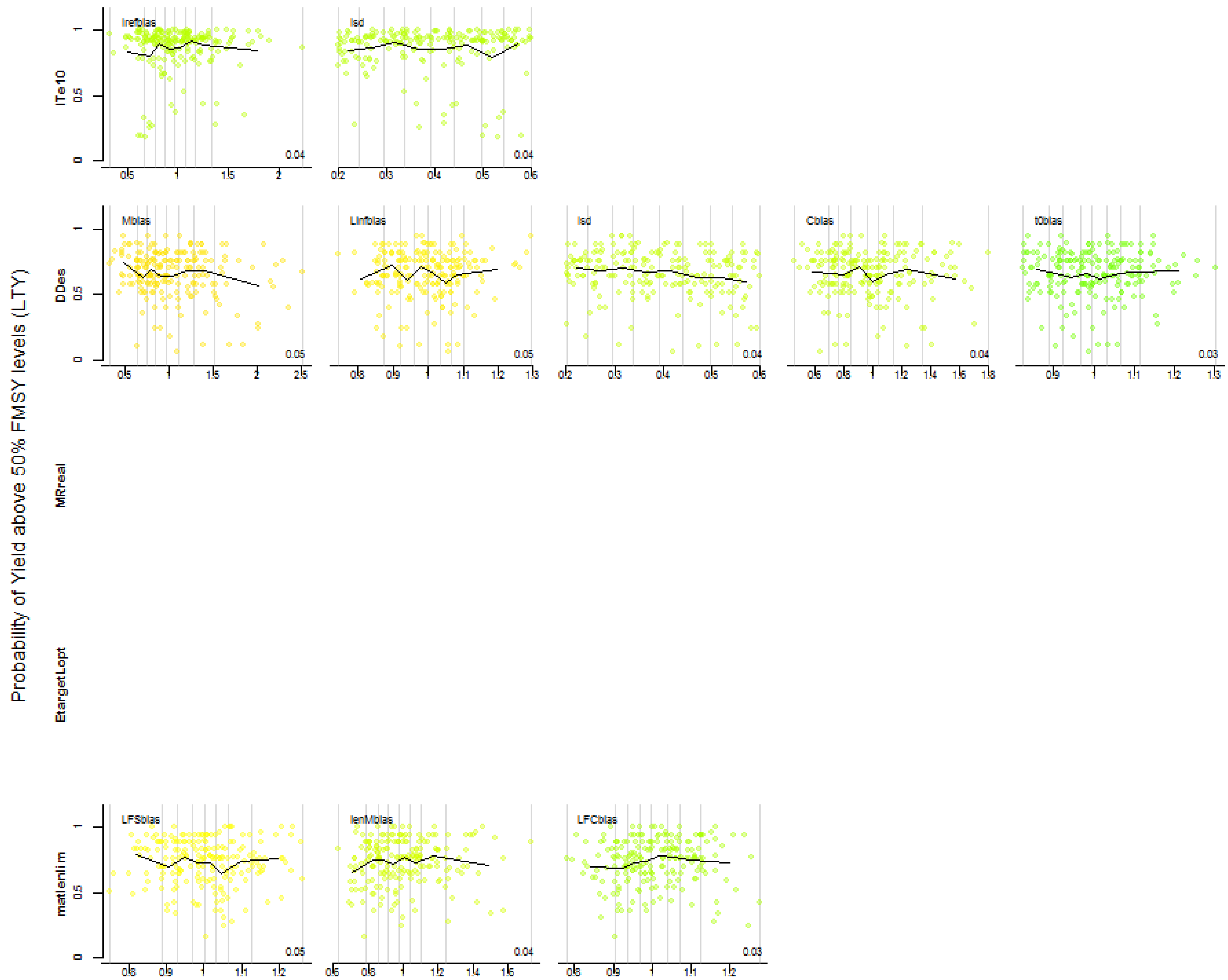

Figure 7. The value of better data for rougheye rockfish top ranking MPs given the yield utility measure LTY. Note that some management procedures do not require data and are prescriptive such as MRreal (closure of area 1 with reallocation of effort to area 2) and EtargetLopt.

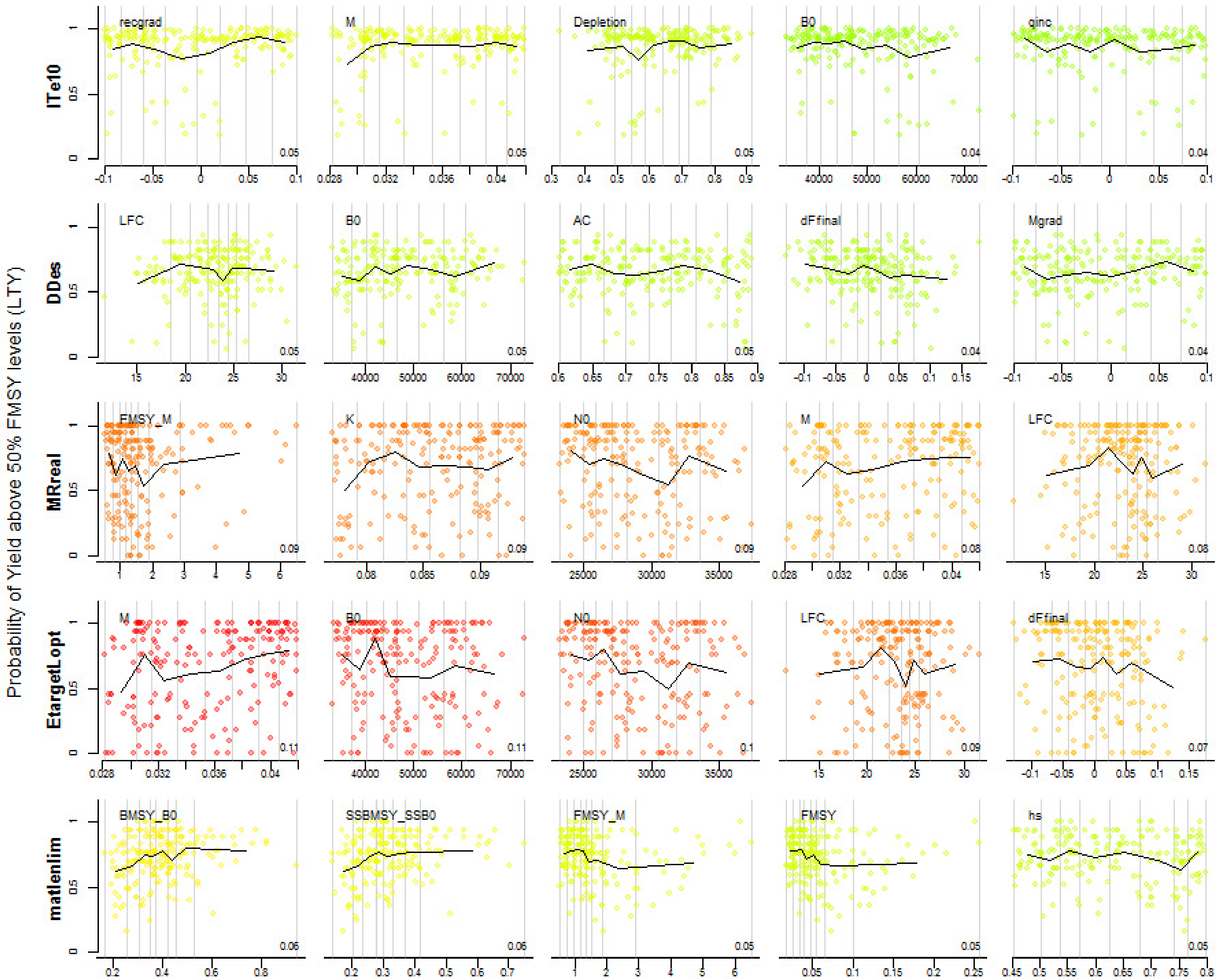

Figure 8. The cost of current uncertainties for rougheye rockfish top ranking MPs given the yield utility measure LTY.

3 Results for Canary Rockfish

3.1 Performance of available management procedures

Given the simulation of a more depleted population than rougheye rockfish, the satisficing for canary rockfish revealed a different range of best performing MPs. Over 100 simulations and 50 projected years, the index target - input control MPs *ITe10* and *ITe5* that were amongst the best performing MPs for rougheye rockfish, did not meet satisficing requirements with respect to biological metric B50 for canary rockfish (Figure 3). Status quo management options were also excluded with the exception of fishing at 75% of current effort (*curE75*).

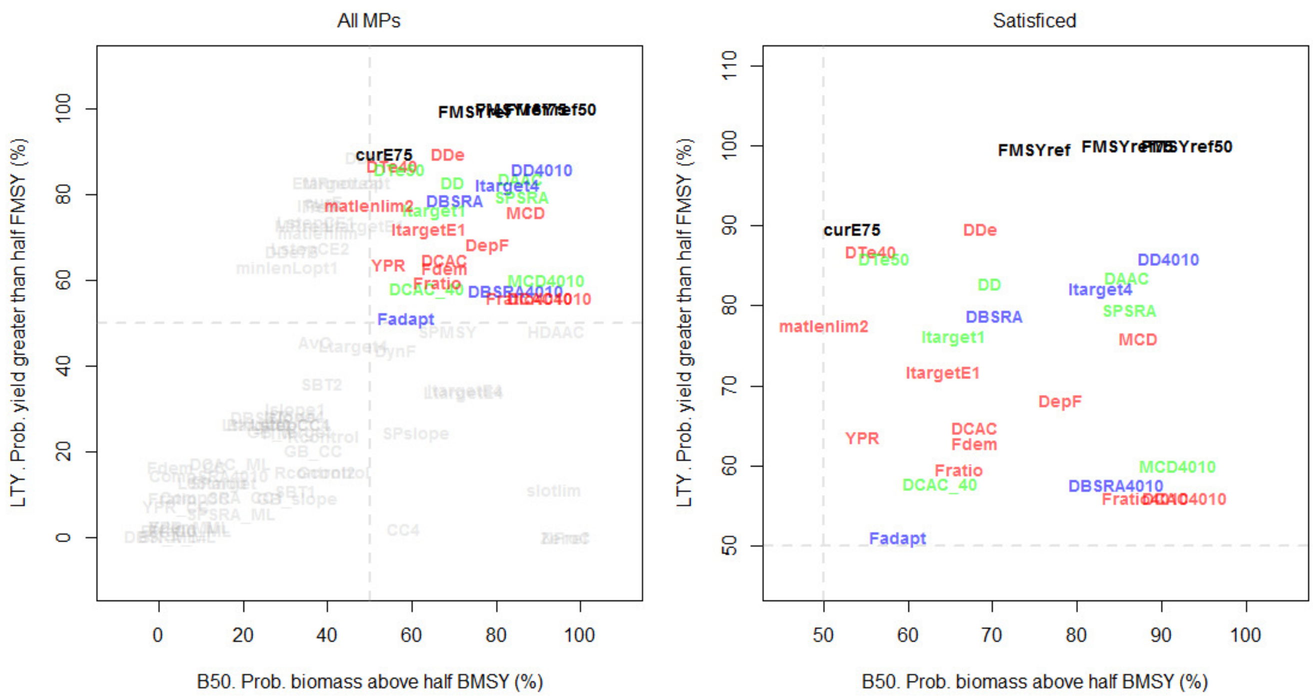

Figure 9. Satisficing of MPs for canary rockfish. A total of 30 MPs passed the satisficing requirements of 80% probability of biomass being over 50% BMSY and 70% probability of yield higher than half FMSY yield (dashed lines). MPs that did not meet the satisficing requirements are shaded in grey in the left hand panel. These satisficing requirements were arbitrary and chosen only to reduce the total number of MPs to a manageable set for more detailed analysis. MPs colored black are reference MPs such as current effort and FMSY. The other color coding is arbitrary and simple to improve legibility. The simulations in this case were run for 50 projected years and only 100 simulations were used to generate the metrics (MPs rankings were stable, Appendix V).

The more detailed MSE analysis ran for 84 years which was three mean generation times (MGT = 28 years) since this was less than the maximum of 100 projected years used in the detailed rougheye rockfish MSE analysis.

Similarly to the rougheye rockfish MSEs, the longer projection period (84 vs 50 years) led to somewhat worse performance of all MPs. The more detailed MSE analysis reveals the relatively strong performance of simple stock assessment methods such as delay-difference models *DDe*[8] and *DD4010*[9] (Figure 10). The *DD4010* MP obtained very similar yield performance to the *DDe* MP but with substantially higher probability of remaining above 50% BMSY (90% as opposed to 60% for *DDe*). Marginal benefits in terms of the B50 metric could be obtained using the *MCD4010*[10] and

[8] *DDe* is a 3 parameter deterministic delay difference assessment conditioned on a time series of catch and effort (or survey) data that makes effort recommendations to keep fishing at FMSY levels.
[9] *DD4010* is a delay different assessment coupled with a 40-10 harvest control rule that provides catch advice.
[10] *MCD4010* is a Mean Catch Depletion method (Harford and Carruthers 2017) that sets a catch limit to 2 x stock depletion x average historical catches. In this version this is subject to additional throttling by a 40-10 control rule

DCAC4010[11] MPs but these came at the cost of a large reduction in the probability of obtaining half FMSY yield (around a 25 point reduction to around 55%).

Other data-limited MPs provided similar performance to the best performing *DD4010* MP such as *DAAC*[12], *Itarget4* [13]and *SPSRA*[14].

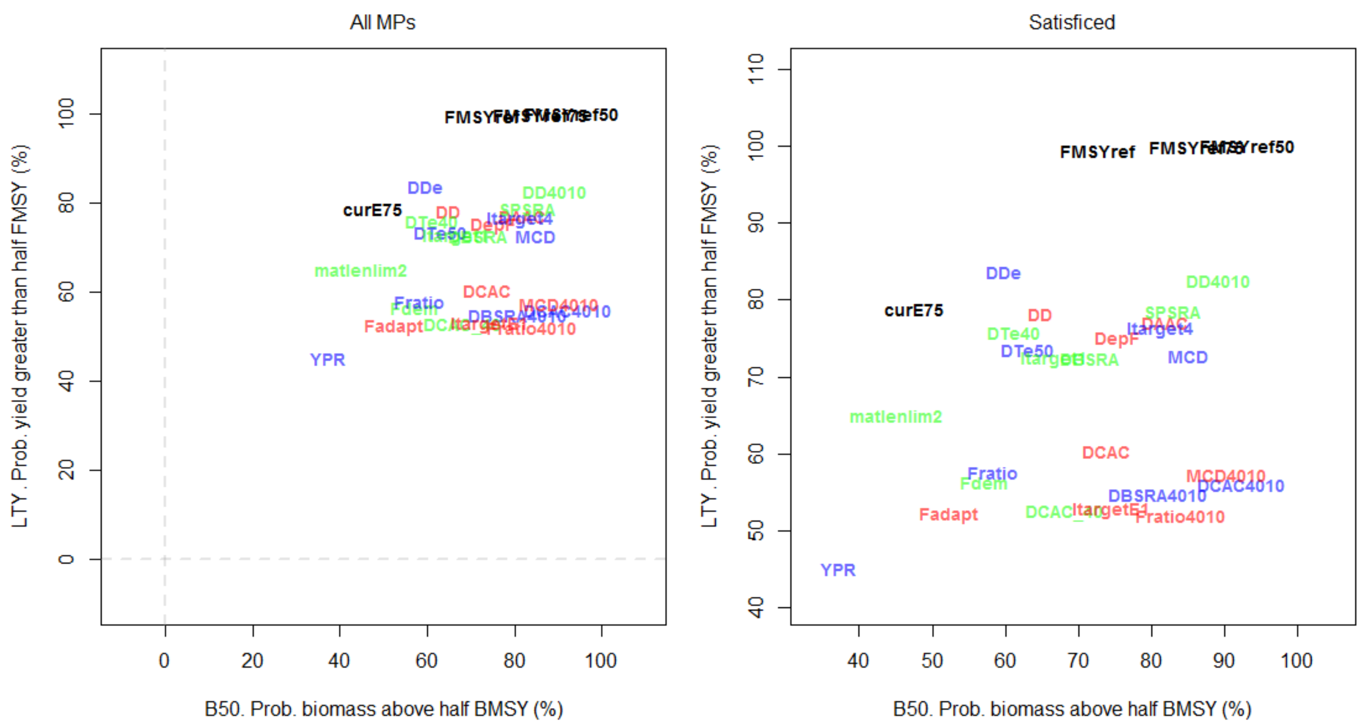

Figure 10. Detailed MSE analysis for canary rockfish. MPs colored black are reference MPs such as current effort and FMSY. The other color coding is arbitrary and simple to improve legibility. The simulations in this case were run for 100 projected years and 200 simulations were used to generate the metrics (absolute performance of MPs was stable, Appendix V)

[11] *DCAC4010* is Depletion Corrected Average Catch of MacCall (2009) with additional throttling by a 40-10 control rule.
[12] *DAAC* is depletion adjusted average catch which uses the DCAC as a proxy for MSY and sets a catch limit equal to DCAC x depletion x 2
[13] *Itarget4* makes adjustments to catch limits to achieve a target relative abundance index level
[14] *SPSRA* is similar to DBSRA (Dick and MacCall 2011) but sets a catch limit by a surplus production stock reduction analysis

3.2 Evaluation by COSEWIC criteria

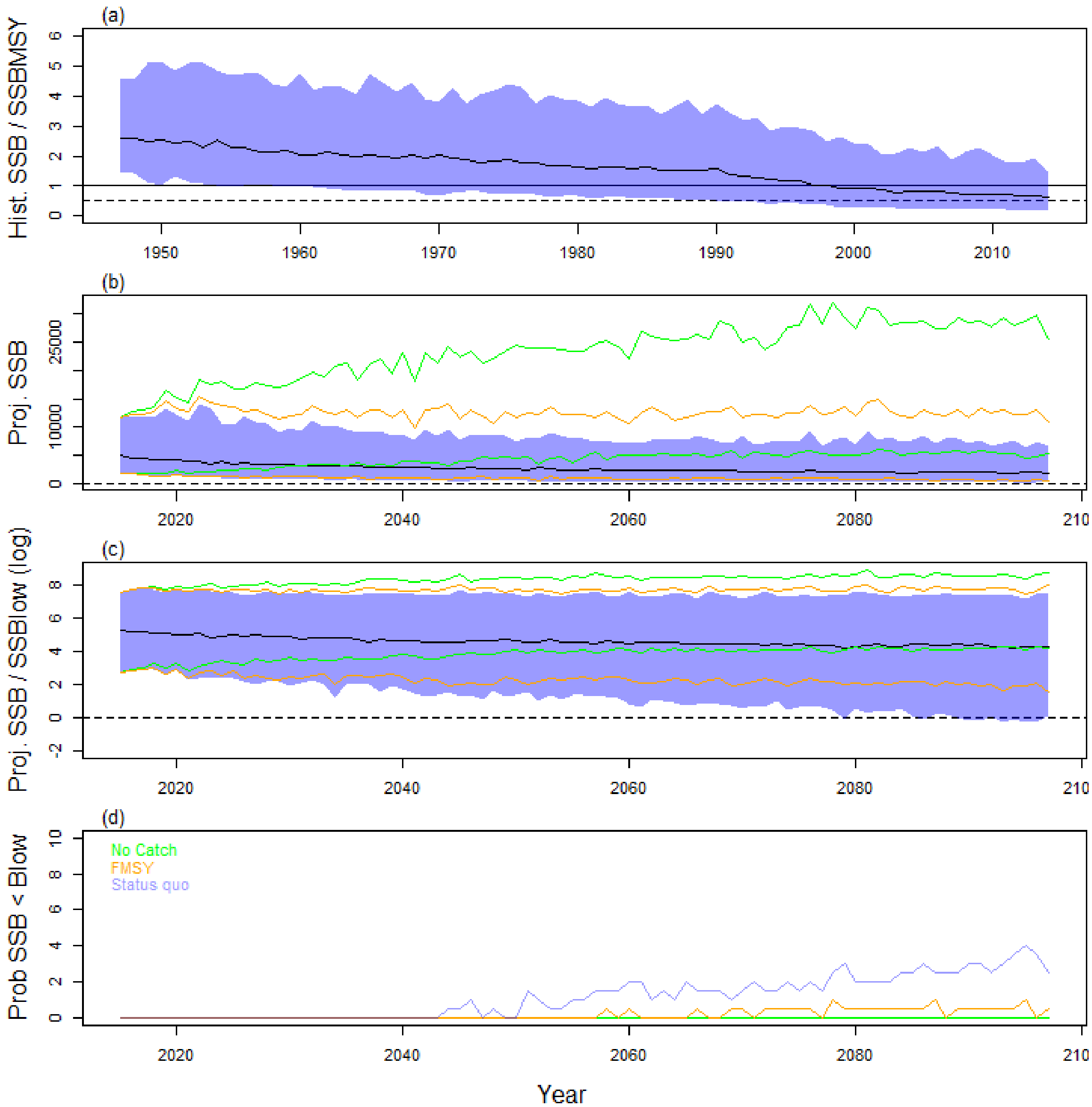

Figure 11. Population trajectories for canary rockfish. Panel a shows historical model predicted SSB relative to SSB at MSY levels. Panel b shows projected SSB under status quo exploitation rates, fishing at FMSY and also zero fishing (no catch). Panel c shows the projected SSB relative to a very low biomass level (Blow) where it would take 3 generation times to reach half of SSB at MSY with zero catches. Panel d shows the projected probability of SSB dropping below the Blow threshold.

1. Evaluate present species status for abundance, range and number of populations.

Operating models for canary rockfish were conditioned on the outputs (depletion, exploitation rate trends, parameters) of the most recent stock assessment for canary rockfish (Stanley et al. 2009). The current status of the stock is relatively uncertain but DLMtool reconstruction places this in the range of around 0.25 – 1.5 SSBMSY with depletion (from the assessment) in the range of 12% - 35% of unfished levels (95% probability interval) (Figure 11, panel a).

Outside the scope of this study: 'range and number of populations'

2. Evaluate recent species trajectory for abundance, range, and number of populations.

The stock assessment infers steady decline in spawning biomass with the mean trend declining from 2.5 times BMSY levels to around 0.5 times BMSY levels in 2006 (Figure 11, panel a).

Outside the scope of this study: 'range and number of populations'

3. Estimate, to the extent that information allows, the current or recent life history parameters for the species (total mortality [Z], natural mortality [m], fecundity, maturity, recruitment, etc.) or reasonable surrogates, and associated uncertainties for all parameters.

These were not estimated in this analysis and operating models were parameterized from (Stanley et al. 2006). Readers are directed to that document for more detailed account of assessment model estimates.

4. Address the separate terms of reference for describing and quantifying (to the extent possible) the habitat requirements and habitat use patterns of the species.

Outside the scope of this study.

5. Estimate expected population and distribution targets for recovery, according to DFO guidelines.

Spawning biomass levels relative to MSY and 50% MSY levels are presented in Figure 11 panel a.

6. Project expected population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current population dynamics parameters and associated uncertainties using DFO guidelines on long-term projections.

In the case of rougheye rockfish, mean generation time (the average age of an adult in the unfished population) is 27.9 requiring a projection of 84 years.

Current fishing levels are predicted to lead to continued declines in SSB over the next 84 years and to a greater extent that fishing at FMSY levels.

Projections estimate a high probability (~98%) of the stock dropping below BMSY levels by the end of the 84-year projection (Figure 11 panel b).

The likelihood of declines to lower than *Blow* levels at the end of the projection is around 4% (Figure 11 panels c and d).

7. Evaluate residence requirements for the species, if any.

Outside the scope of this study.

8. Assess the probability that the recovery targets can be achieved under current rates of population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

The assessment estimates that current exploitation rates are higher than FMSY levels and therefore operating model projections predict future declines substantially below BMSY levels. Figure 11 (panels b, c and d) show that reductions in fishing mortality rate to FMSY levels may reduce biomass reductions markedly particularly the likelihood of dropping below the *Blow* reference point).

9. Quantify to the extent possible the magnitude of each major potential source of mortality identified in the pre-COSEWIC RAP and considering information in the COSEWIC Status Report, from DFO sectors, and other sources

Outside the scope of this study.

10. Quantify to the extent possible the likelihood that the current quantity and quality of habitat is sufficient to allow population increase, and would be sufficient to support a population that has reached its recovery targets (using the same methods as in step 4).

Outside the scope of this study.

11. Assess to the extent possible the magnitude by which current threats to habitats have reduced habitat quantity and quality.

Outside the scope of this study.

12. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all feasible measures to minimize/mitigate the impacts of activities that are threats to the species and its habitat (steps 9 and 11).

Alternative management procedures are identified and evaluated in Section 3.1 above.

13. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all reasonable alternatives to the activities that are threats to the species and its habitat (steps 9 and 11), but with potential for less impact. (e.g. changing gear in fisheries causing bycatch mortality, relocation of activities harming habitat).

Alternative management procedures are identified and evaluated in Section 3.1 above.

14. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all reasonable and feasible activities that could increase the productivity or survivorship parameters (steps 3 and 8).

Outside the scope of this study.

15. Estimate, to the extent possible, the reduction in mortality rate expected by each of the mitigation measures in step 12 or alternatives in step 13 and the increase in productivity or survivorship associated with each measure in step14.

Alternative management procedures are identified and evaluated in Section 3.1 above.

16. Project expected population trajectory (and uncertainties) over three generations (or other biologically reasonable time), and to the time of reaching recovery targets when recovery is feasible; given mortality rates and productivities from 15 that are associated with specific scenarios identified for exploration. Include scenarios which provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.

Projections for status quo exploitation rate, FMSY fishing and zero fishing are provided in Figure 11 (panels b, c and d)

17. Recommend parameter values for population productivity and starting mortality rates, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.

This is the objective of defining operating models and is covered in detail in Appendix II. Also see Value of Information, Section 3.3 below.

3.3 Value of information

In contrast to the rougheye value of information analysis, the performance of the top ranking canary rockfish MPs can be strongly determined by both the quality of data and uncertainty in operating model parameters. For example both *SPSRA* and *DAAC* methods see pronounced reductions in B50 as depletion information becomes positively biased (*Dbias*) (Figure 12); the overly optimistic view of stock depletion leading to overexploitation. Note that depending on the source of depletion information, positive biases of between 2 and 3 are not improbable (comparable to hyperstability beta parameter of 1.5 over 50 years).

For these MPs, the pattern is reversed for yield metrics which see a strong decline in LTY with negative bias in depletion (Figure 14), which is to be expected as this overly pessimistic view of stock level leads to chronic underfishing. Given the range of depletion biases that were simulated, these results suggest a particular vulnerability of the SPSRA and DAAC MPs.

As simulated, the delay difference MPs (*DDe* and *DD4010*) were relatively robust with respect to their observation processes. In these MPs, depletion information is coming from an effort time series that is subject to relatively little hyperstability or hyperdepletion. This appears inconsistent with the biases simulated for depletion that is used by the SPSRA and DAAC MPs (if such good stock trend information were available, wouldn't this also be available for SPSRA and

DAAC MPs?). A more comprehensive review of data quality is required to produce consistent and reasonable results for these MPs.

While the performance of *SPSRA* and *DAAC* MPs were vulnerable to observation processes, they were relatively robust with respect to simulated conditions (Figure 13 and Figure 15). The delay difference assessments on the other hand (*DDe* and *DD4010*) performed worse with respect to B50 when MSY spawning biomass relative to unfished is much higher than assumed by the underlying population dynamics models (*i.e.* the DD MPs generally assume that SSBMSY/SSB0 is around 0.2 to 0.3 and some simulations this can be higher leading to overfishing by these MPs). The yield performance of the delay-difference assessments was not affected by the position of SSBMSY relative to SSB0 however (Figure 8).

3.3.1 Utility according to biomass criteria (B50)

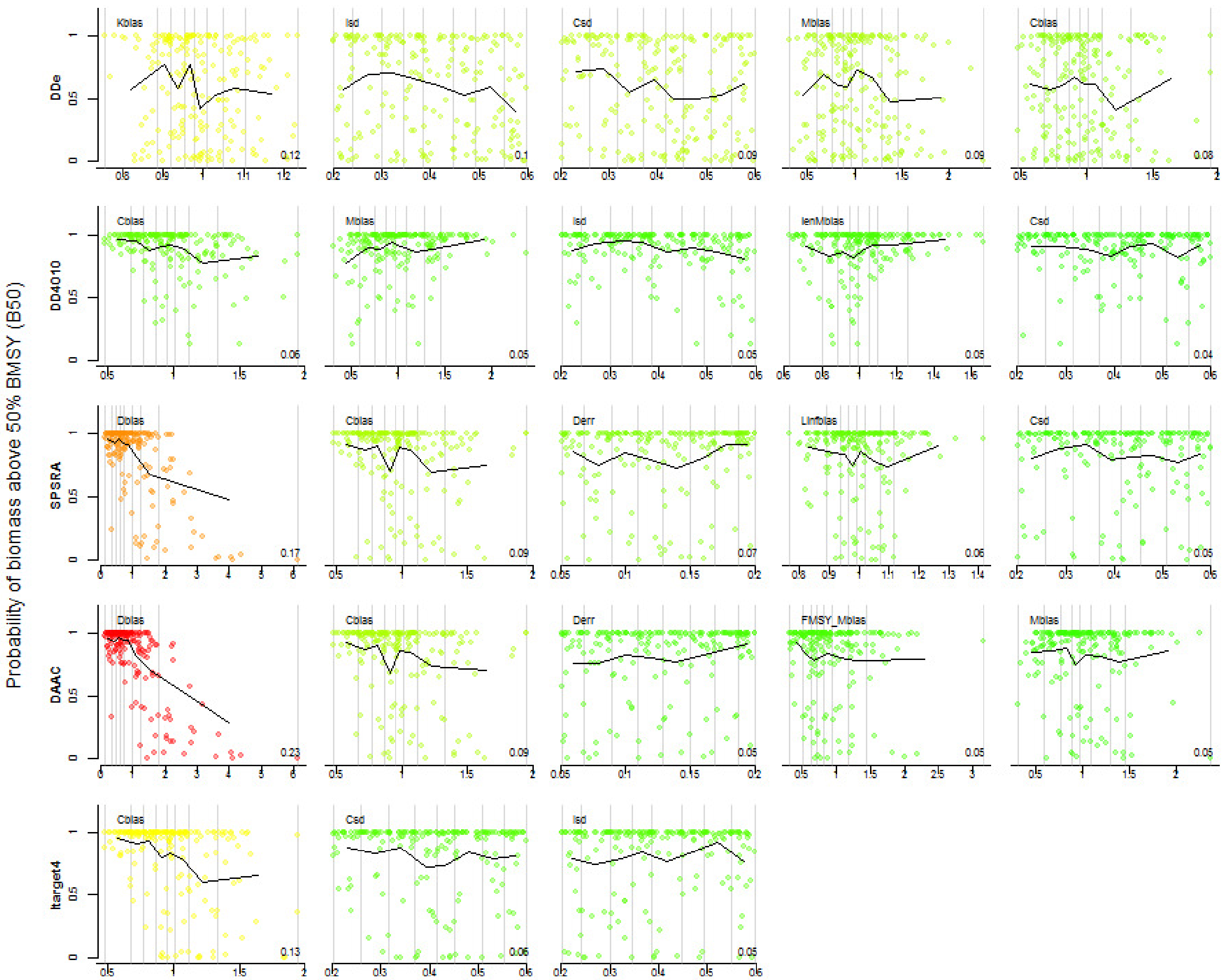

Figure 12. The value of better data for canary rockfish top ranking MPs given the biomass utility measure B50.

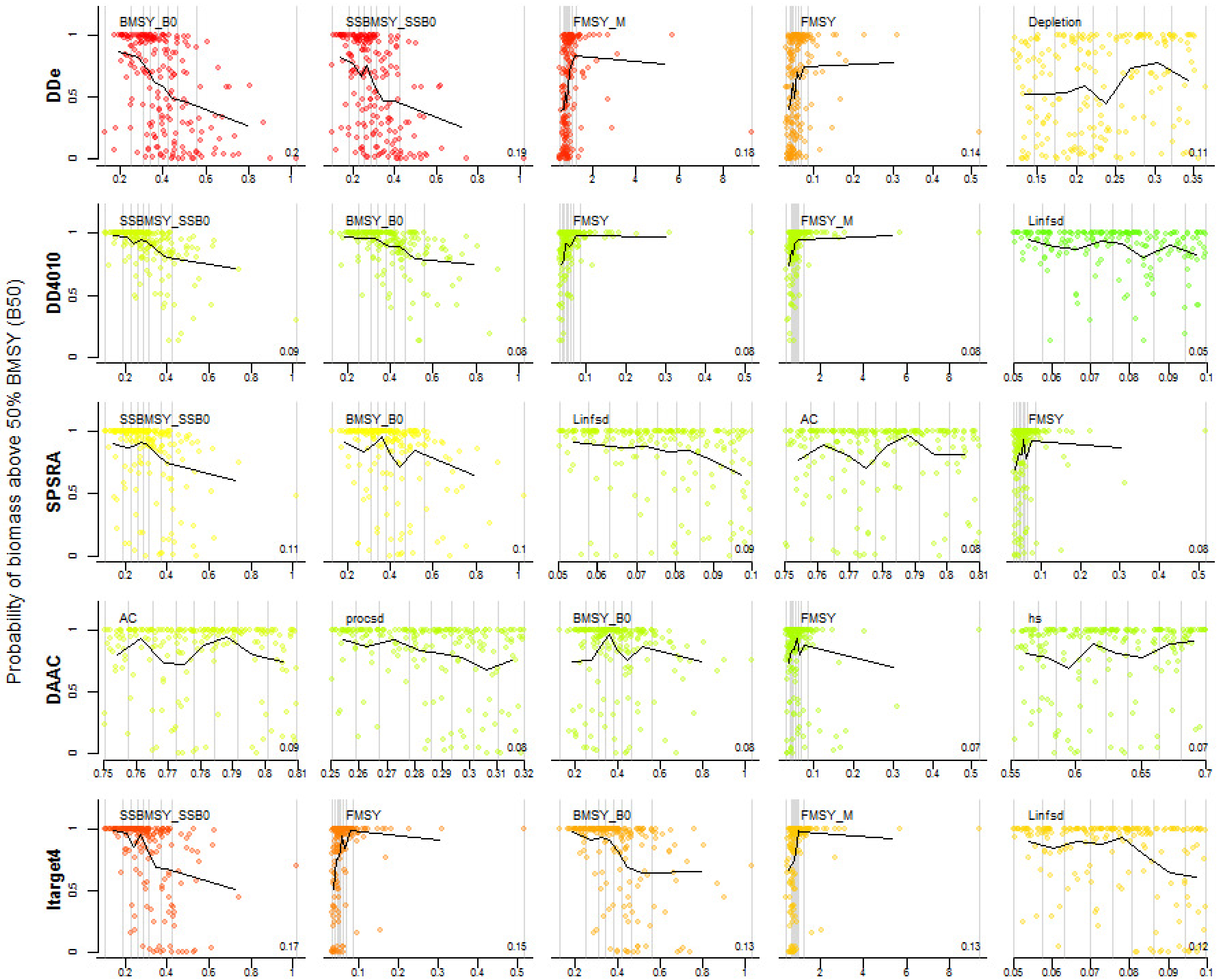

Figure 13. The cost of current uncertainties for canary rockfish top ranking MPs given the biomass utility measure B50.

3.3.2 Utility according to long term yield (LTY)

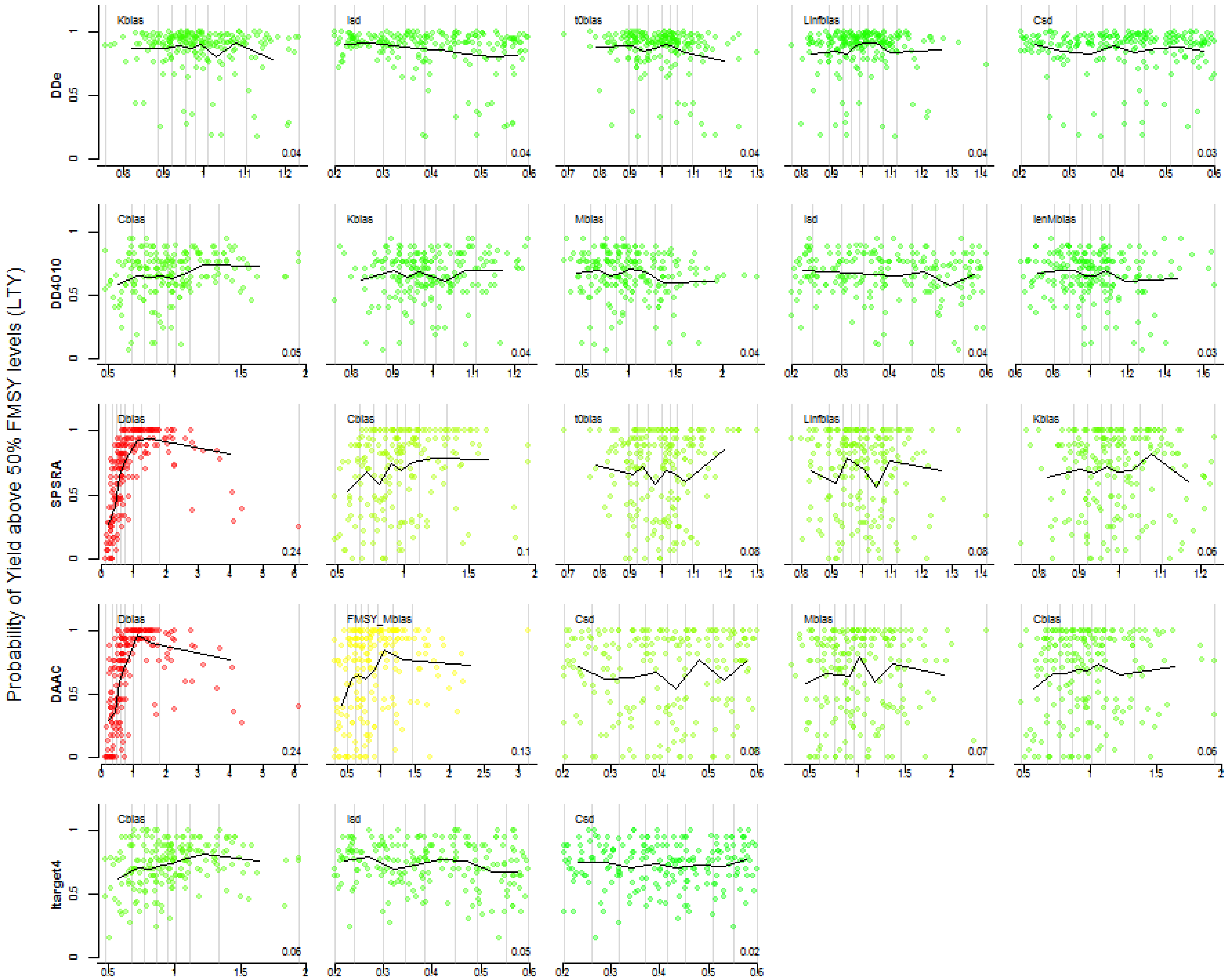

Figure 14. The value of better data for canary rockfish top ranking MPs given the yield utility measure LTY.

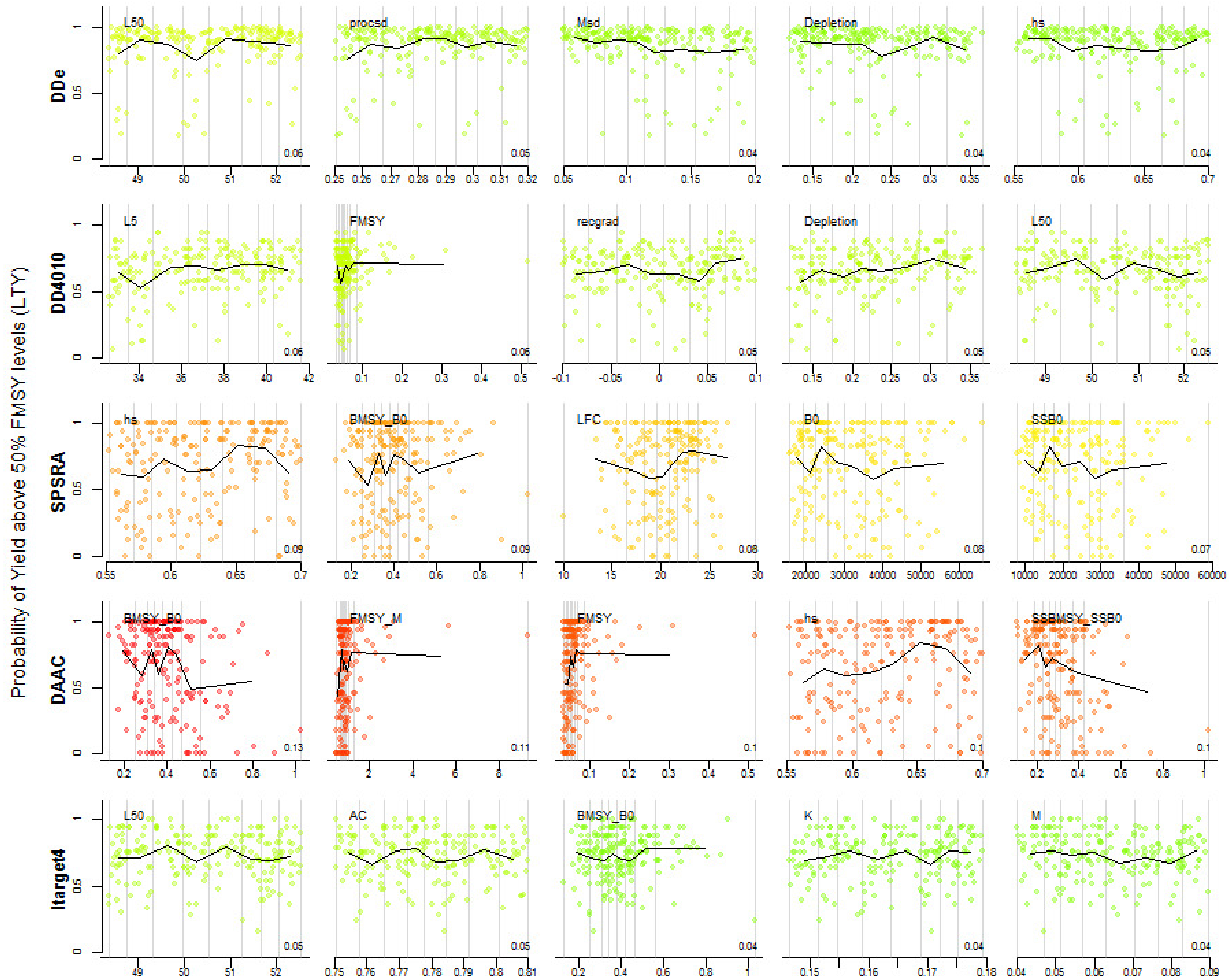

Figure 15. The cost of current uncertainties for canary rockfish top ranking MPs given the yield utility measure LTY.

4 Discussion

This investigation demonstrates that MSE frameworks can be adapted from stock assessments (*e.g*. Stanley *et al*. 2009 for canary rockfish) or derived from similar analyses (stochastic SRA, Walters *et al*. 2006) to test a range of prospective management procedures. Post-hoc analysis of simulations can be used to reveal observation processes and population / fishery parameters that most strongly determined performance in a value of information analysis.

The same MSE framework can be used for the more simple task of conducting projections (typical in stock assessment) to inform COSEWIC assessments. This can include the estimation of quantities to inform these management processes for example the *Blow* reference point.

A core limitation of the MSE approach presented here is that the absolute performance of MPs and their rankings are determined by the simulated quality of data. Since management procedures require a diverse and often contrasting sources of data, if one source (*e.g*. length composition data) is simulated with unrealistically high precision all dependent MPs will obtain an unrealistic boost in performance. It follows that a priority for future MSE analyses of this type is closer scrutiny of the observation error models and the development of protocols for populating these critical inputs.

A relatively concise series of data are simulated in the DLMtool MSE analysis. Future toolkit revisions are to include observation error models for alternative sources of data such as conventional tagging, gene tagging and close-kin genetics analysis which would allow for the investigation of alternative MPs.

It would be desirable to include MPs that better represent the state-space stock assessment models that are typically applied to data-rich stocks. To this end, a series of rapid statistical catch-at-age and state-space delay-difference models are currently under development as part of a separate DFO-UBC project. Unfortunately these were not available for this analysis. Note however that in many cases there was not much room for improvement beyond the more simplistic MPs that were tested (some getting around 90% of the yield and biomass performance of true simulated FMSY). Expectations for the benefit of these more complex MPs should be tempered by these results.

In general the status and outlook for rougheye rockfish was considerably more optimistic than canary rockfish. Relatively good performance could be obtained for rougheye rockfish using simple management procedures and these were robust to uncertainties in data quality and the parameters of the operating model. The MSE results for canary rockfish on the other hand present a stock that is likely to continue to decline at current fishing levels. Consequently simulations suggest that careful selection of management procedures is necessary as these could have important consequences for future biomass trajectories and have varying sensitivities to the quality of data that are available.

The results of the rougheye rockfish simulations and projections were determined strongly by the estimates of stock status and exploitation rate arising from the stochastic SRA analysis. A closer inspection of the data used by this analysis reveals potentially problematic inconsistencies in vulnerability at age over time (Figure 16). While the stochastic SRA method appears to be reliable when well-behaved composition data are simulated (Appendix III), it may not perform well given the irregular patterns in composition that are apparent in Figure 16. A future priority for the rougheye rockfish operating models is either the extension of the stochastic SRA approach to include relative abundance data or robustness testing of MPs subject to alternative ranges for current stock depletion (DLMtool allows the patterns in the estimated fishing mortality rate from the catches and the inferred patterns in recruitment anomalies from stochastic SRA to be tied to alternative depletion scenarios).

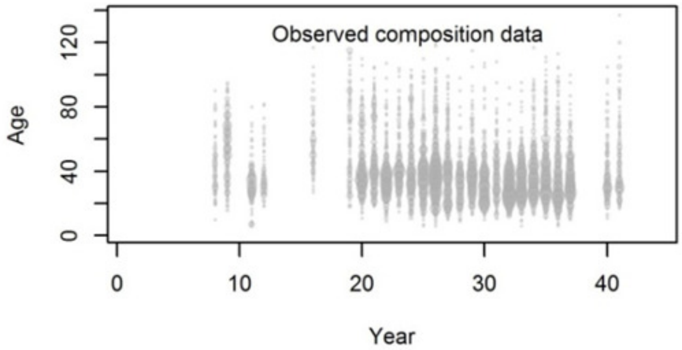

Figure 16. Catch-at-age composition data used to inform stock depletion, unfished stock size, fishing mortality rates and recruitment deviations using Stochastic SRA.

Effort controls (*e.g*. days fishing, set hours) were among the top performing MPs for rougheye rockfish. The credibility of this result rests on a defensible model for potential changes in catchability (fishing efficiency) over time and density dependent catchability phenomenon (that attributed to stock collapses in effort control fisheries in New England for example). Currently the operating models for rougheye and canary rockfish assume minimal potential changes in catchability, simulating changes in the range of -0.1 to 0.1 % per year. A research priority is developing these models to include more representative fishing dynamics and therefore better represent the relative performance of MPs that manage by effort limits versus catch limits.

5 Acknowledgments

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7 Appendix I: Operating model specification for Rougheye Rockfish

Attached to this document.

8 Appendix II: Operating model specification for Canary Rockfish

Attached to this document.

9 Appendix III: Development and testing of a Stochastic Stock Reduction Analysis for specifying operating models

9.1 Overview

Before using the stochastic SRA to define operating models for rougheye rockfish, the approach was simulation tested with respect to a number of life-history types to confirm correct coding of the population dynamics and likelihood functions, likelihood weightings and implementation of the MCMC algorithm. Rather than providing a lengthy description of the method here, readers are directed to Walters et al. 2006 which is a very similar approach.

Below are the results of the simulation testing for two life-history types of moderate and higher longevity (snapper and rockfish respectively). The rock fish life history type has additional simulation tests for varying qualities and quantities of catch-at-age composition data. The default simulation setting generated 100 observations of catch-at-age each year for all years of the fishery.

9.2 Snapper life-history (moderately long-lived)

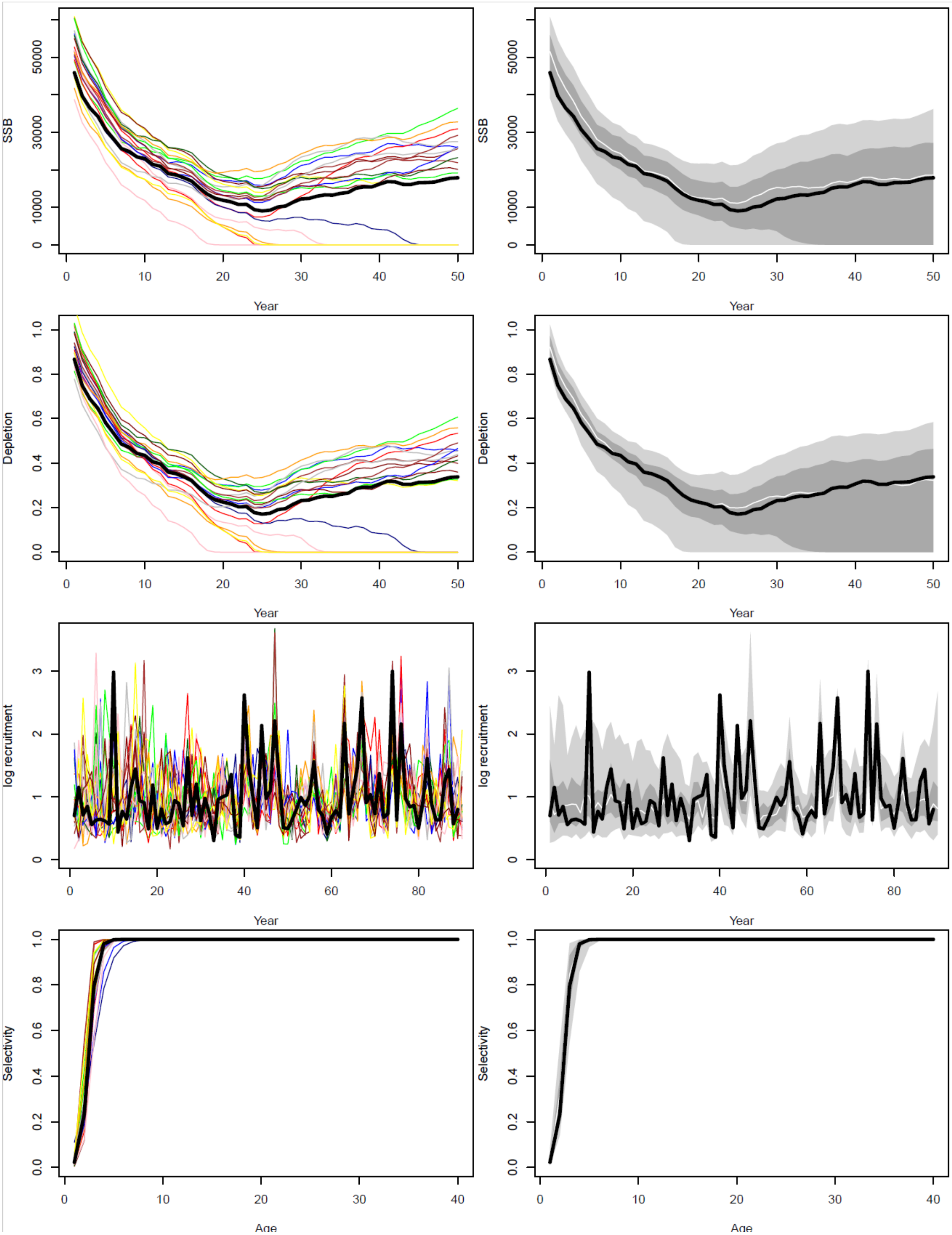

Figure 17. Simulation testing the stochastic SRA DLMtool function for the snapper life-history type. The solid black line is the true simulated time-series. On the left hand column of panels, 10 different estimated series are plotted. All of the estimated series are summarized on the right hand column of panels that show the median (white line), interquartile range (dark shaded area) and the 2.5 - 97.5 percentile range (light shaded area).

9.3 Rockfish life history (long lived)

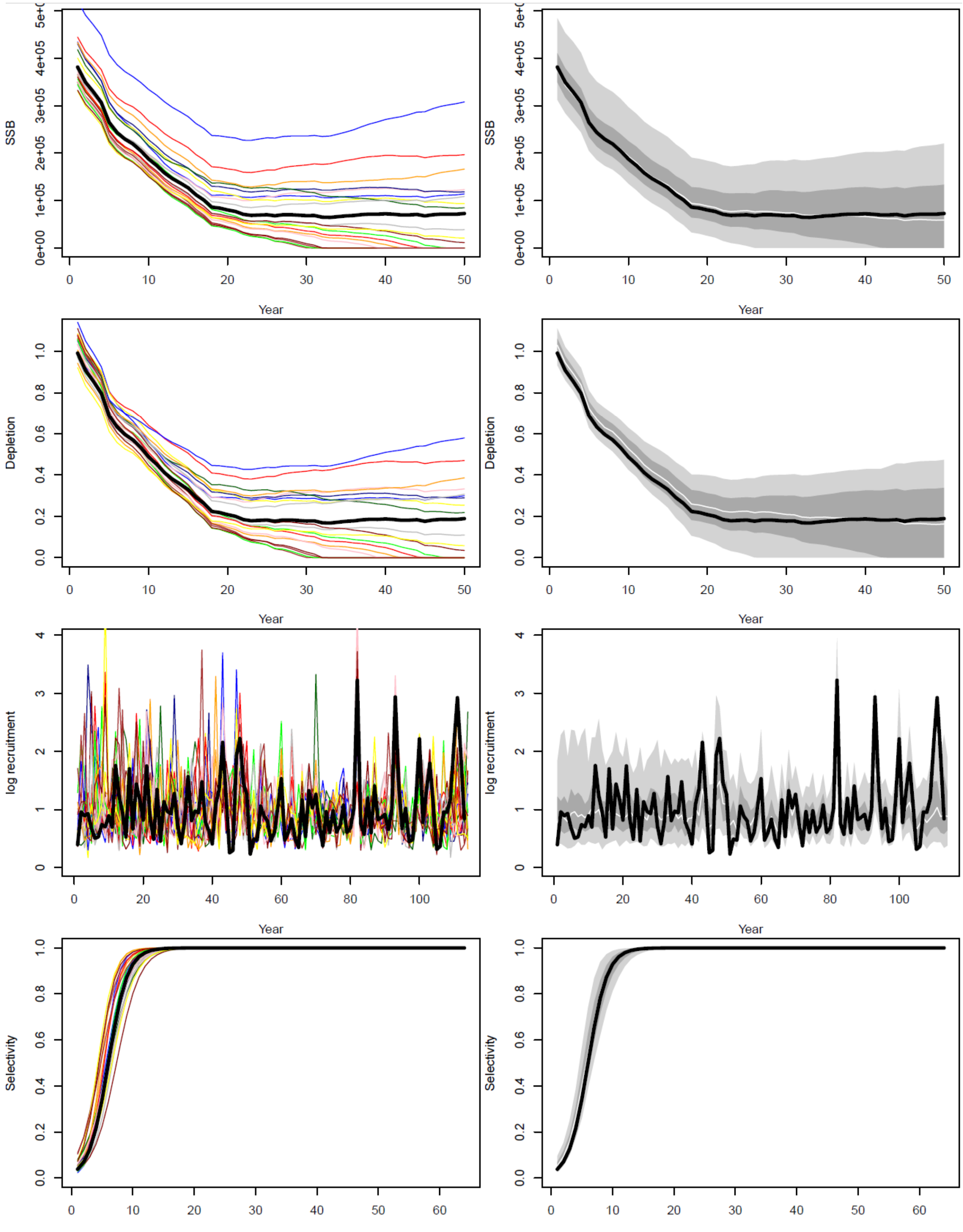

Figure 18. Simulation testing the stochastic SRA DLMtool function for the rockfish life history type. As Figure 17.

9.4 Rockfish life history, catch-at-age data for the most recent 5 years only

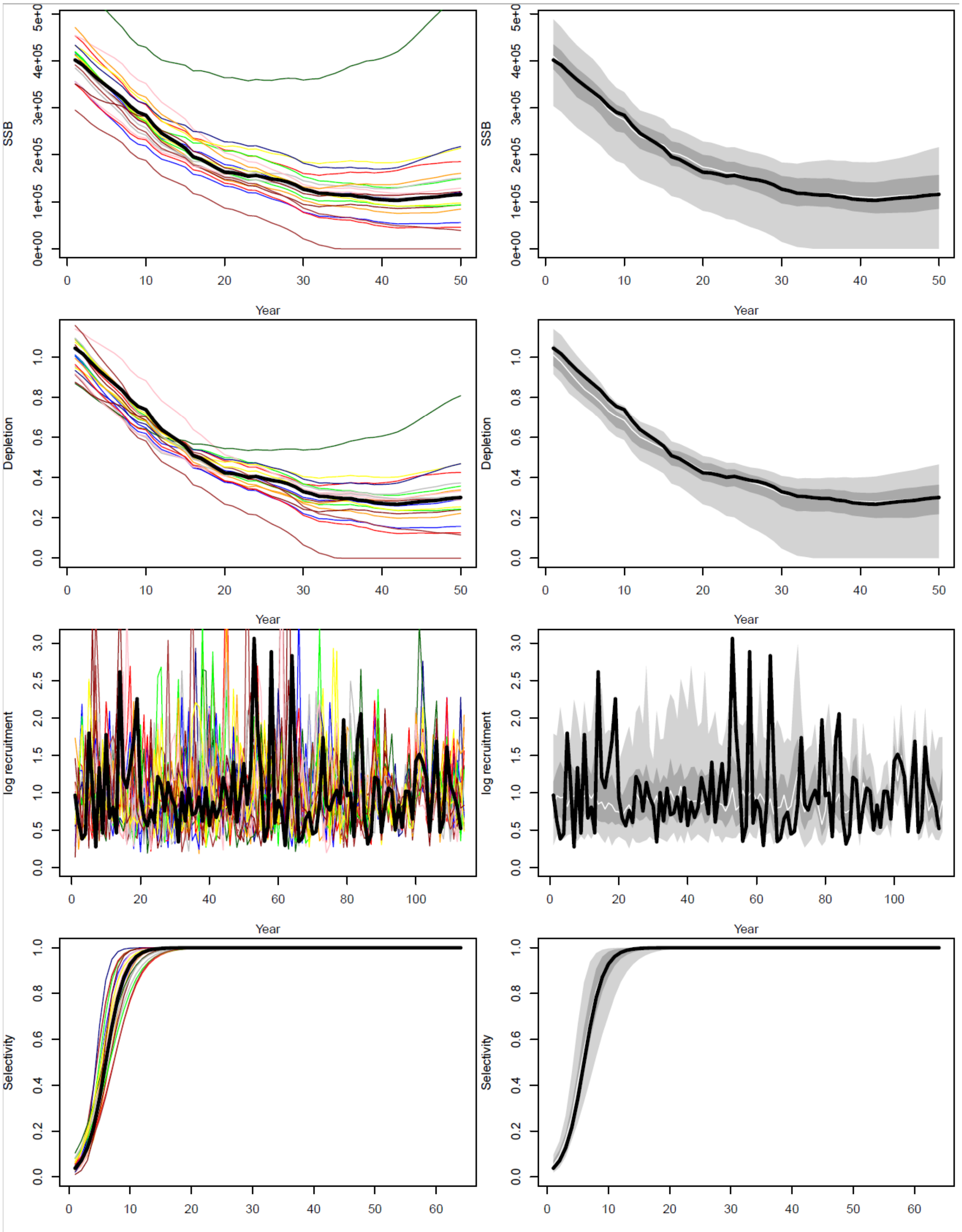

Figure 19. Simulation testing the stochastic SRA DLMtool function for the rockfish life history type where catch-at-age composition data are only available for the last 5 years. As Figure 17.

9.5 Rockfish life history, catch-at-age data for the most recent 5 years only, half (50) observations of catch-at-age per year.

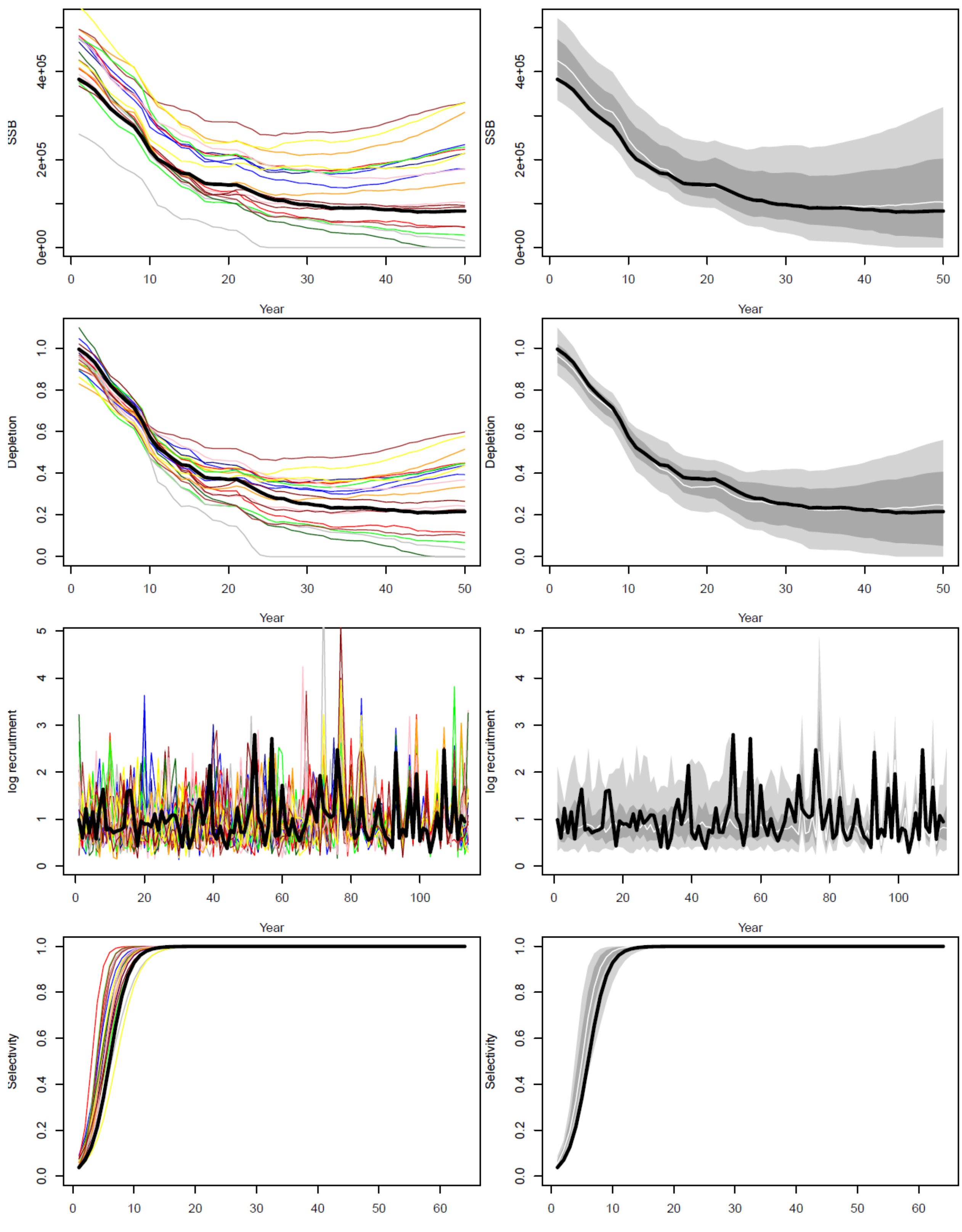

Figure 20. Simulation testing the stochastic SRA DLMtool function for the rockfish life history type where catch-at-age composition data are only available for the last 5 years. As Figure 17.

9.6 Evaluation

In general it appears that the Stochastic SRA function is unbiased and can be expected to bracket the true simulated value of stock depletion, selectivity pattern and historical recruitment strength (Figure 17 - Figure 19). Only when relatively few annual observations of catches were provided over a relatively short recent time period, did the algorithm start to estimate mean trends that were substantially different from those simulated (ie Figure 20)

10 Appendix IV: Convergence diagnostics

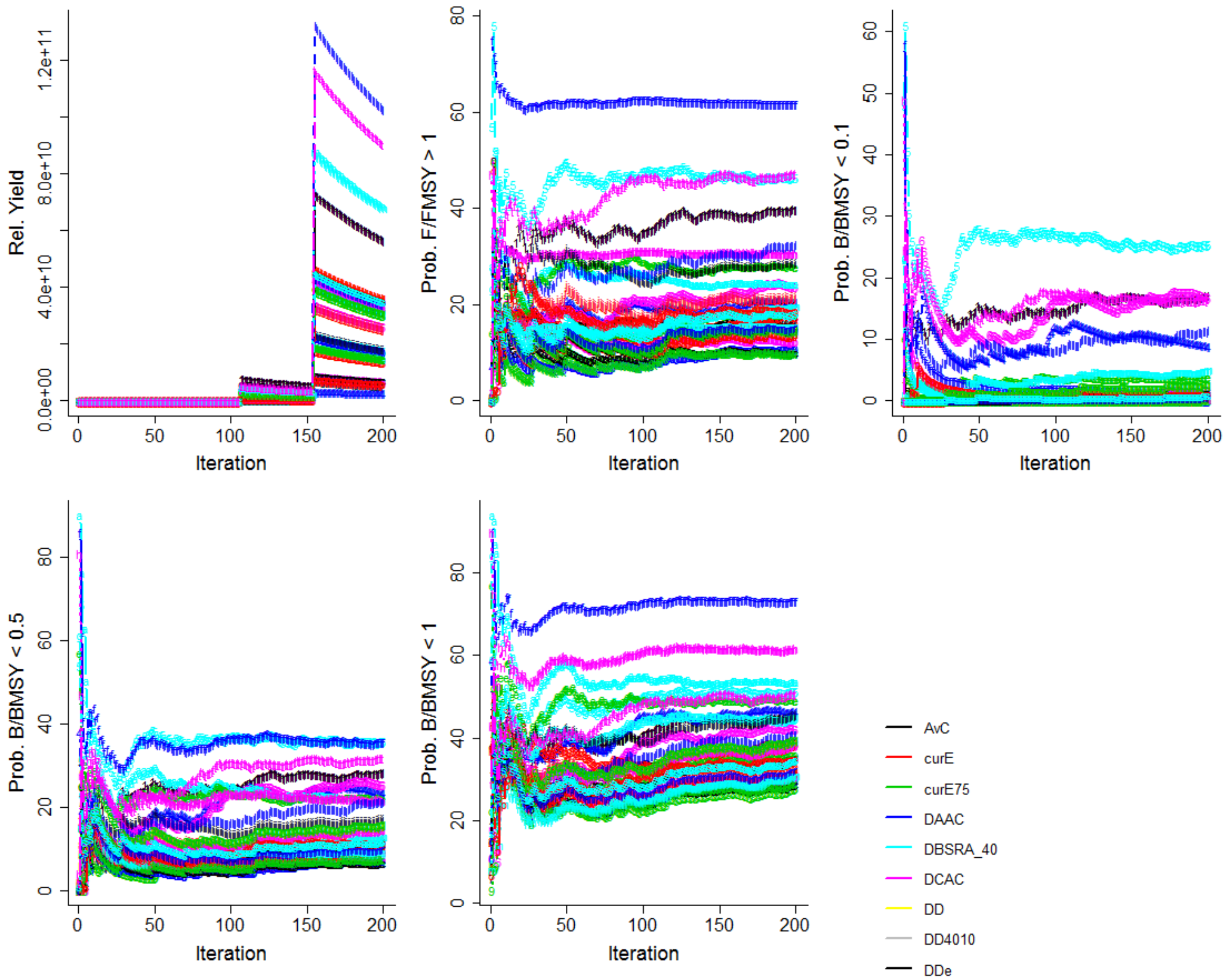

Figure 21. Convergence diagnostics for the detailed run of the rougheye rockfish MSE

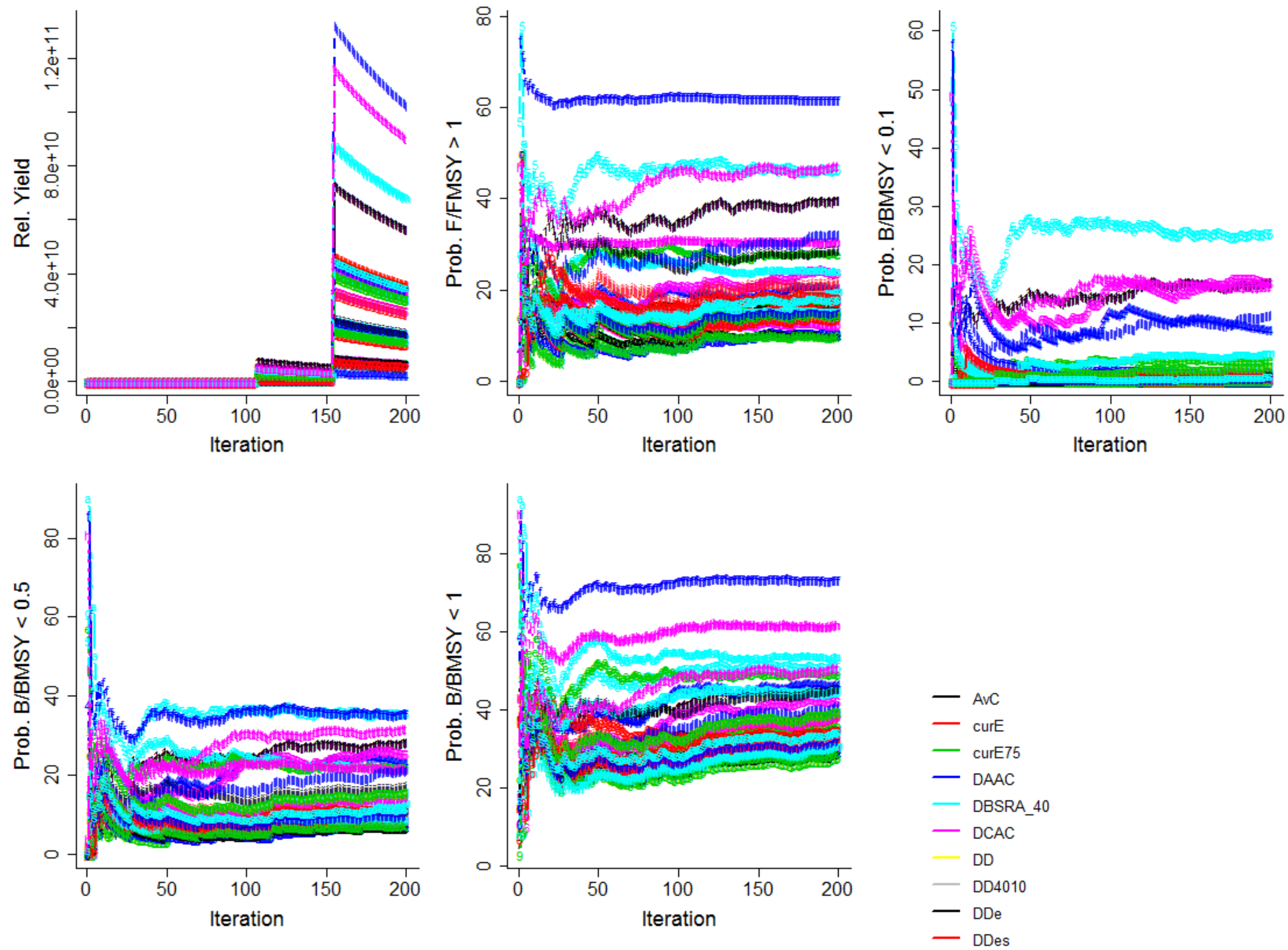

Figure 22.Convergence diagnostics for the detailed run of the canary rockfish MSE